ECE566
Enterprise Storage Architecture

Spring 2025

File Systems

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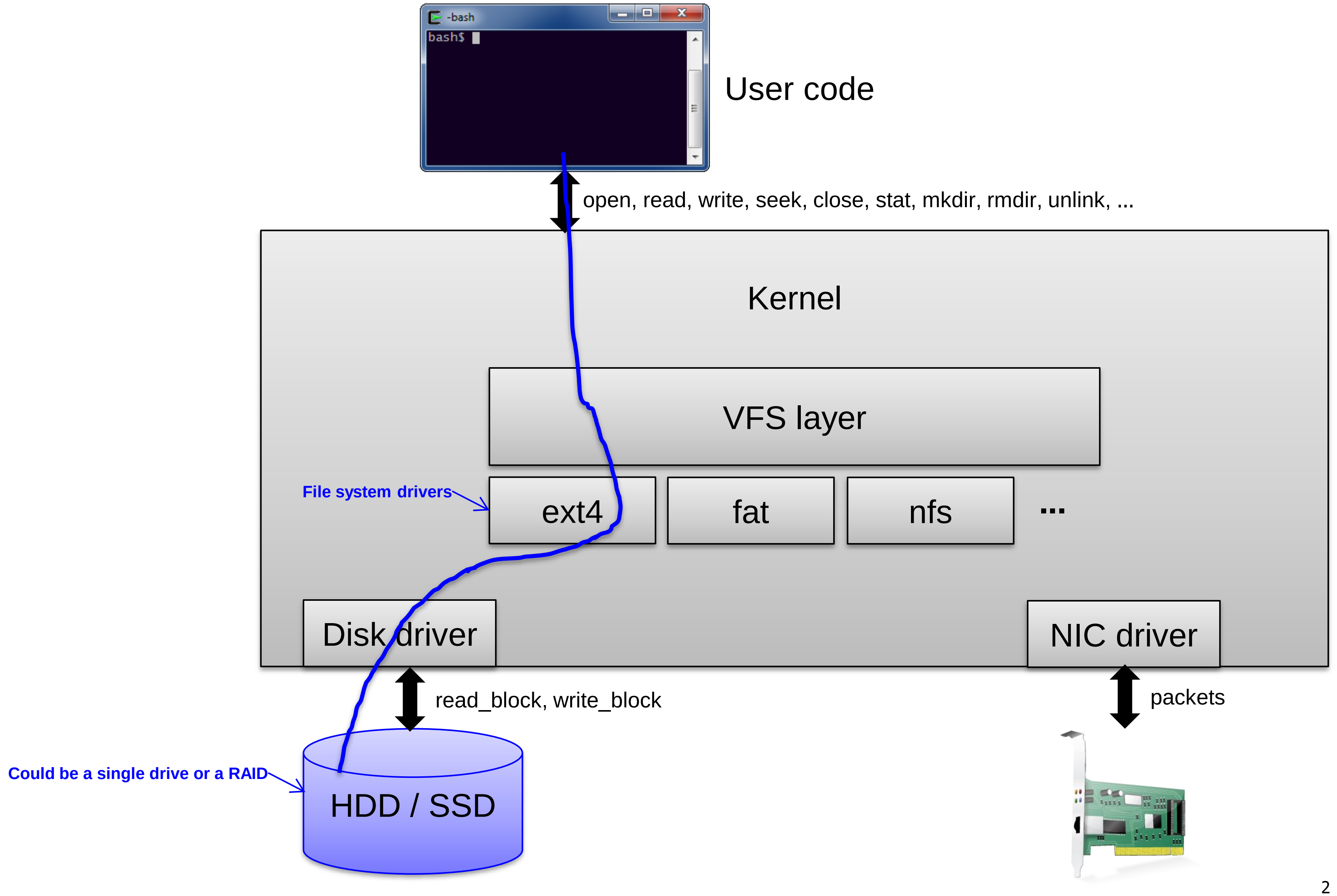
The file system layer

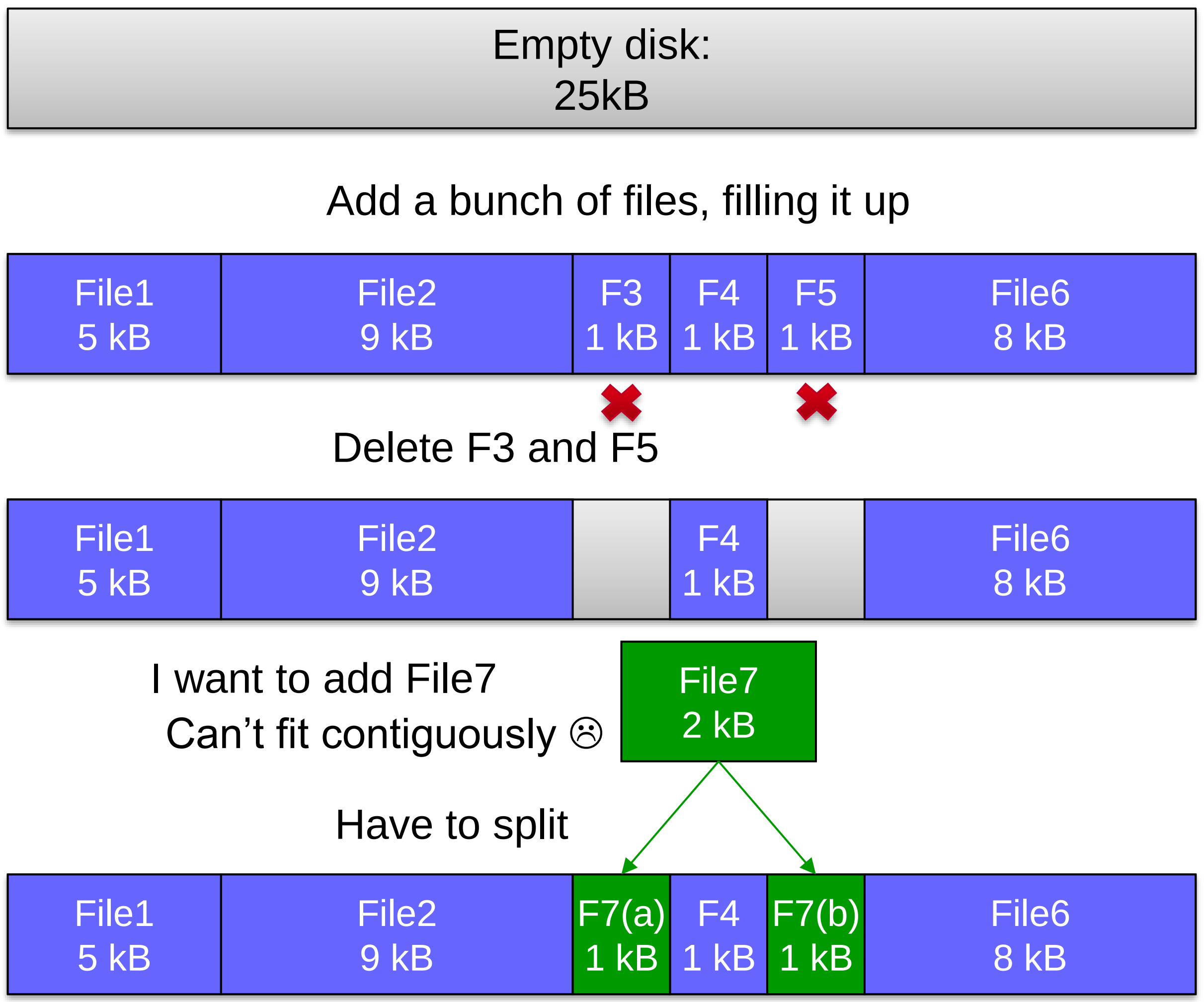


High-level motivation

- Disks are dumb arrays of blocks.
- Need to **allocate/deallocate** (claim and free blocks)
  - Want to maximize **locality** (similar stuff is close together)
  - Ideally keeping data **contiguous** (sequential data is sequential on disk)
  - Minimize **fragmentation** (see next slide)
- Need **logical containers** for blocks (allow delete, append, etc. on different buckets of data – *files*)
- Need to **organize** such containers (how to find data – *directories*)
- May want to **access control** (restrict data access per user)
- May want to dangle additional features on top

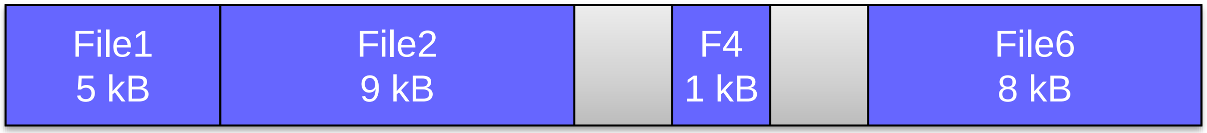
*Result: **file systems***

Disk allocation

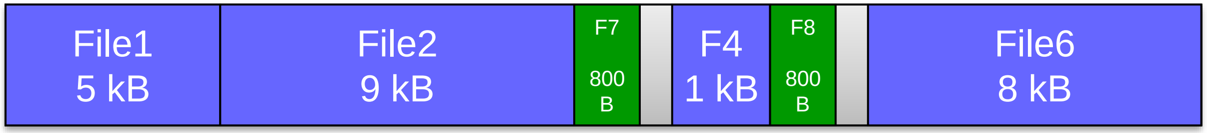


It gets worse: external fragmentation

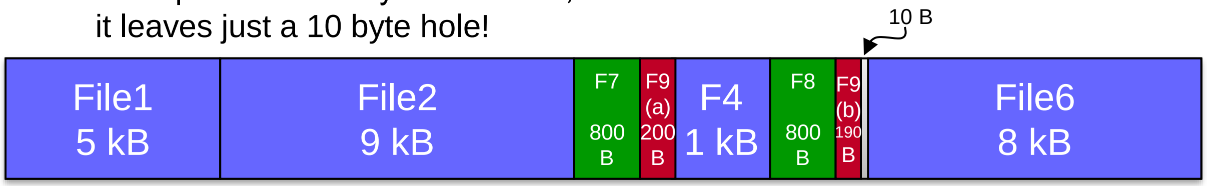
Note: Assume base-10 kB on this slide



I want to add F7 and F8, but they're not a "nice" size, so we leave really tiny holes

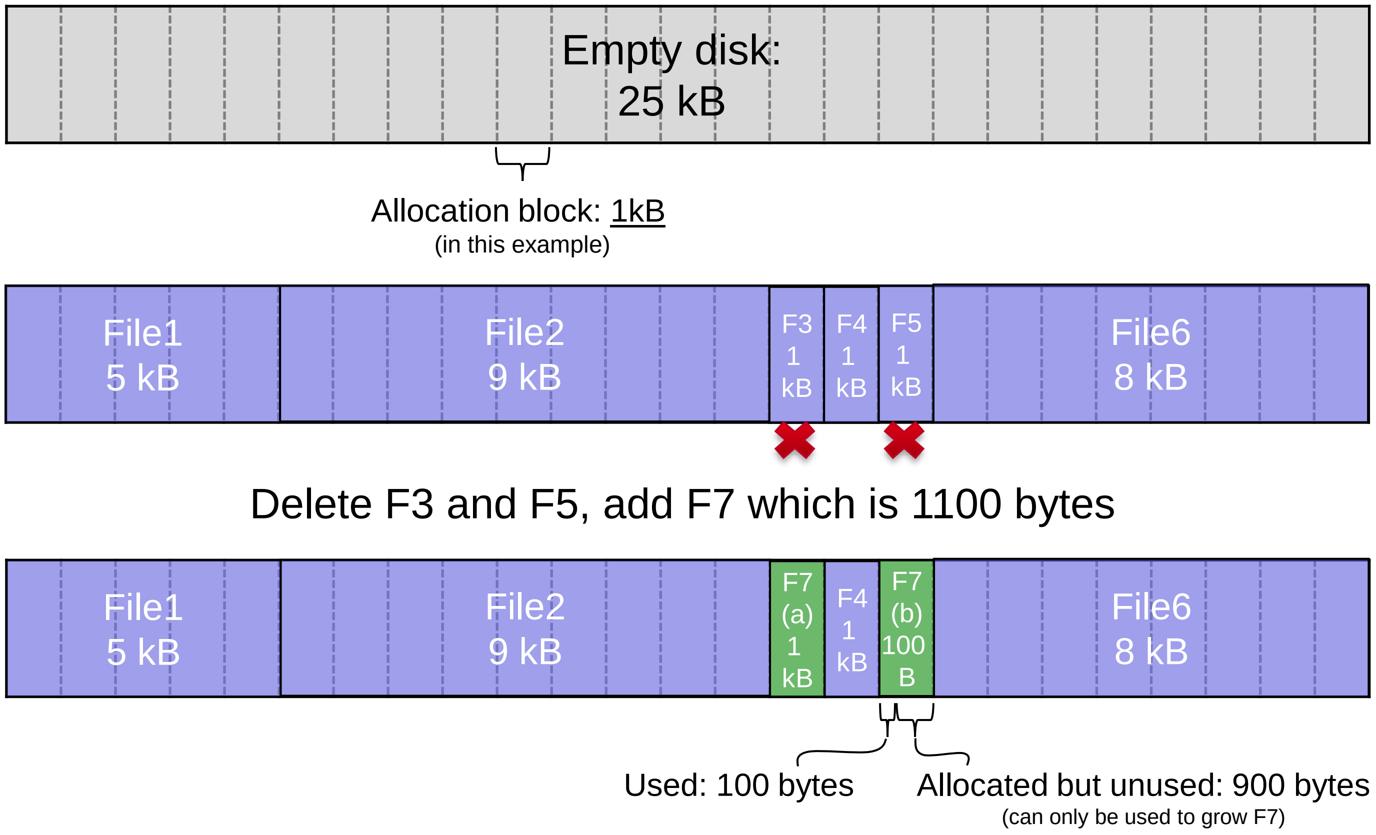


Worse, if a file is a little larger than the hole, then you get a really tiny extra piece. Let's say F9 is 390 B, it leaves just a 10 byte hole!



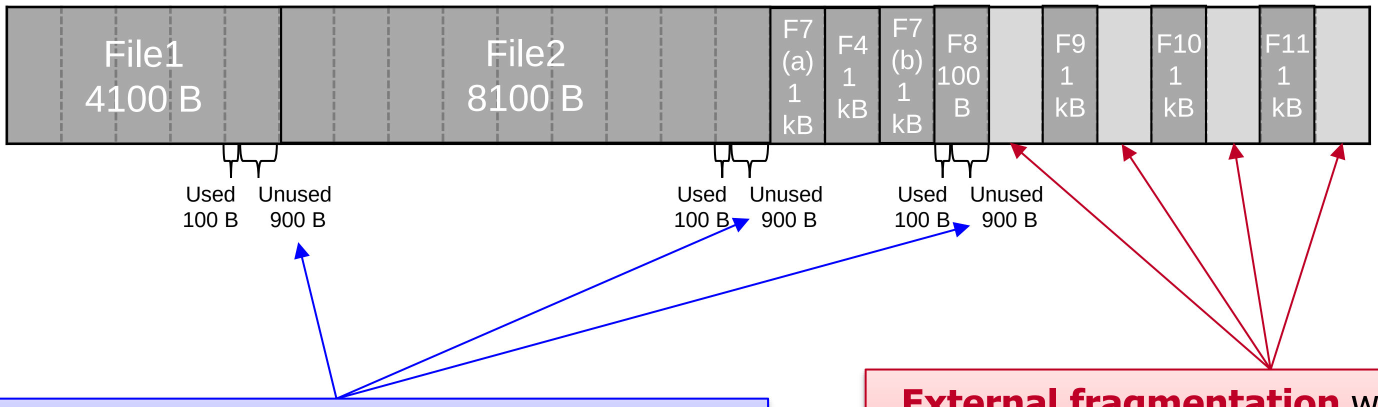
- This is **external fragmentation**: little regions just outside of what has been allocated.
- It can get worse and worse…how to avoid?
  - Minimum contiguous allocation: **blocks** of disk (AKA sectors or clusters)

Also: there's internal fragmentation



- **Pro**: Holes can't get smaller than the block size – lower bound on how small fragments can get (limits performance loss)
  - This is critical, so we do it this way – block allocation is almost always used
- **Con**: Can have a lot of "unusable" space (internal fragmentation)
  - It's allocated but not used

We live with both forms of fragmentation



Internal fragmentation on the tails of files.
Worse if you have lots of small files.

External fragmentation when unallocated blocks are sprinkled across the disk.
Worsens as filesystem ages and files are added/deleted.

- Internal fragmentation is mostly just accepted
  - We'll learn techniques to reduce space loss later on (added complexity)
- External fragmentation can be reduced with good filesystem design
  - Can explicitly reverse this by *defragmenting* a disk – reorganizing it (done on HDD, never on SSD)

Disk file systems

- All have same goal:
  - Fulfill file system calls (open, seek, read, write, close, mkdir, etc.)
  - Store resulting data on a block device, and do it *well* (max locality, min fragmentation, etc.)
- The big (non-academic) file systems
  - **FAT ("File Allocation Table")**: Primitive Microsoft filesystem for use on floppy disks and later adapted to hard drives
    - FAT32 (1996) still in use (default file system for USB sticks, SD cards, etc.)
    - Bad performance, poor recoverability on crash, but near-universal and easy for simple systems to implement
  - **ext2, ext3, ext4**: Popular Linux file system.
    - Ext2 (1993) has **inode**-based on-disk layout – much better scalability than FAT
    - Ext3 (2001) adds **journaling** – much better recoverability than FAT
    - Ext4 (2008) adds various smaller benefits
  - **NTFS**: Current Microsoft filesystem (1993).
    - Like ext3, adds **journaling** to provide better recoverability than FAT
    - More expressive metadata (e.g. Access Control Lists (ACLs))
  - **HFS+**: Current Mac filesystem (1998), also has **journaling**.
  - **exFAT**: A modern take on FAT, designed for broad compatibility on stuff like SD cards.
  - "Next gen" file systems: **ZFS** (2005)**, btrfs** (2009)**, WAFL** (1998), and others
    - Block indirection allows snapshots, copy-on-write clones, and deduplication
    - Often, file system handles redundancy itself – no separate RAID layer

FAT

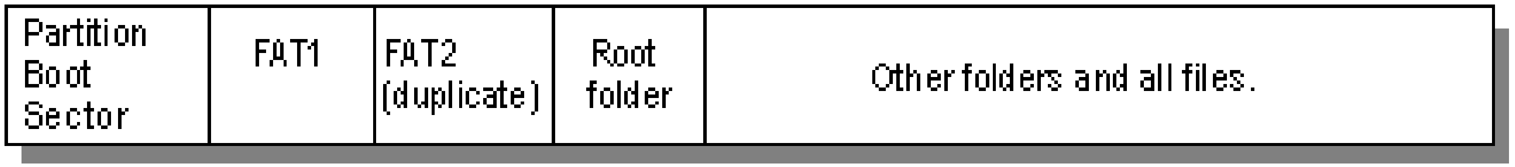
FAT

- FAT: "File Allocation Table"
- 3 different varieties: FAT12, FAT16, FAT32 – to accommodate growing disk capacity

- Allocates by **clusters** (a set of contiguous disk sectors)
  - Clusters number is a power of two < 2^{16}

Cluster is just their term for "block"

- The actual File Allocation Table (FAT):
  - Resides at the beginning of the volume
  - Two copies of the table
  - For a given cluster, gives next cluster (or FFFF if last)



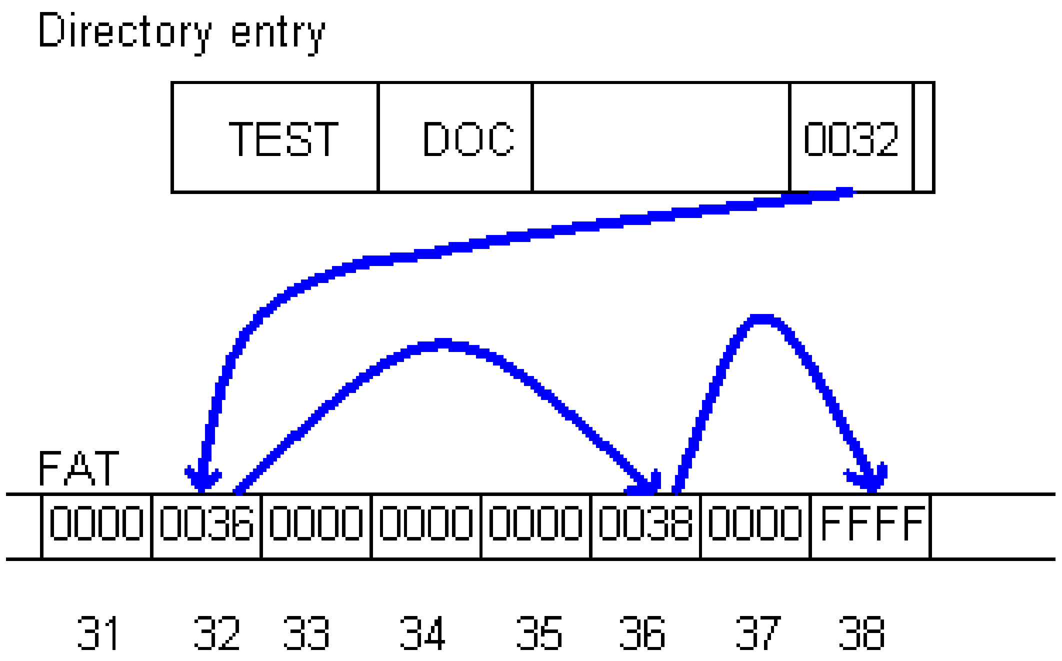
Directories

- Root directory:
  - A fixed length file (in FAT16, FAT32)
- Subdirectories are files of same format, but arbitrary size (extend via the FAT)
- Consist of 32B entries:

Offset	Length	Meaning
0x00	8B	File Name
0x08	3B	Extension
0x0b	1B	File Attribute
0x0c	10B	Reserved: (Create time, date, access date in FAT 32)
0x16	2B	Time of last change
0x18	2B	Date of last change
0x1a	2B	First cluster
0x1c	4B	File size.

FAT Principle

- Directory gives first cluster
- FAT gives subsequent ones in a simple table
- Use FFFF to mark end of file.



Adapted from “Computer Forensics: Hard Drive Format” by Thomas Schwarz (Santa Clara Univ)

Tradeoffs

- Cluster size
  - Large clusters waste disk space because only a single file can live in a cluster.
  - Small clusters make it hard to allocate clusters to files contiguously and lead to large FAT.
- FAT entry size
  - To save space, limit size of entry, but that limits total number of clusters.
  - FAT 12: 12 bit FAT entries
  - FAT 16: 16 bit FAT entries
  - FAT 32: 32 bit FAT entries

Long file names

- Needed to add support for filenames longer than 8+3
- Also needed to be backward compatible

- Result: ridiculous but it works
  - Store a bunch of extra “invalid” entries after the normal one just to hold the long file name
  - Set up these entries in such a way that old software will just ignore them
  - Every file has a long name and a short (8+3) name; short name is auto-generated

Problems with FAT

1. **Scalability/efficiency:**
   - Every file uses at least one cluster: internal fragmentation
   - No mechanism to optimize data locality (to reduce seeks): external fragmentation
   - Fixed size FAT entries mean that larger devices need larger clusters; problem gets worse
2. **Consistency**: What happens when system crashes/fails during a write? Nothing good...
3. **Like a billion other things**: Seriously, did you see the long filename support? It's awful. And there is literally no security model – no permissions or anything. There's just a "hidden" bit (don't show this unless the user really wants to see it) and a "system" bit (probably don't delete this but you can if you want to). It's impossible to support any kind of multi-user system on FAT, so Windows basically didn't until NT, which didn't become mainstream until Windows 2000 and later XP. Also, the way you labeled a whole file system was a special file that had a special permission bit set – that's right, there's a permission bit for "this file is not really a file but rather the name of the file system". Also, the directory entries literally contain a "." entry for the current directory, which is completely redundant. Speaking of redundant data, the duplicate FAT has no parity or error recovery, so it only helps you if the hard drive explicitly fails to read a FAT entry, not if there's a bit error in data read. Even so, if the disk does fail to read the first FAT, the second only helps if the duplicate has the entry you need intact. But recall that bad sectors tend to be clustered, so a failure of one part of the FAT usually means the whole FAT region is dead/dying. This meant scores of FAT data was lost to relatively small corruptions, because file recovery is almost impossible if all disk structure information is lost. In any case, we haven't even got to the other backwards compatibility stuff in FAT32. In that format, the bytes that make up the cluster number aren't even contiguous! They sacrificed some of the reserved region, so just to compute the cluster number you have to OR together two fields. Worst thing of all is that despite all this, FAT32 is still alive and well with no signs of going away, because it's so common that every OS supports it and it's so simple that cheap embedded hardware can write to it. We live in a nightmare.

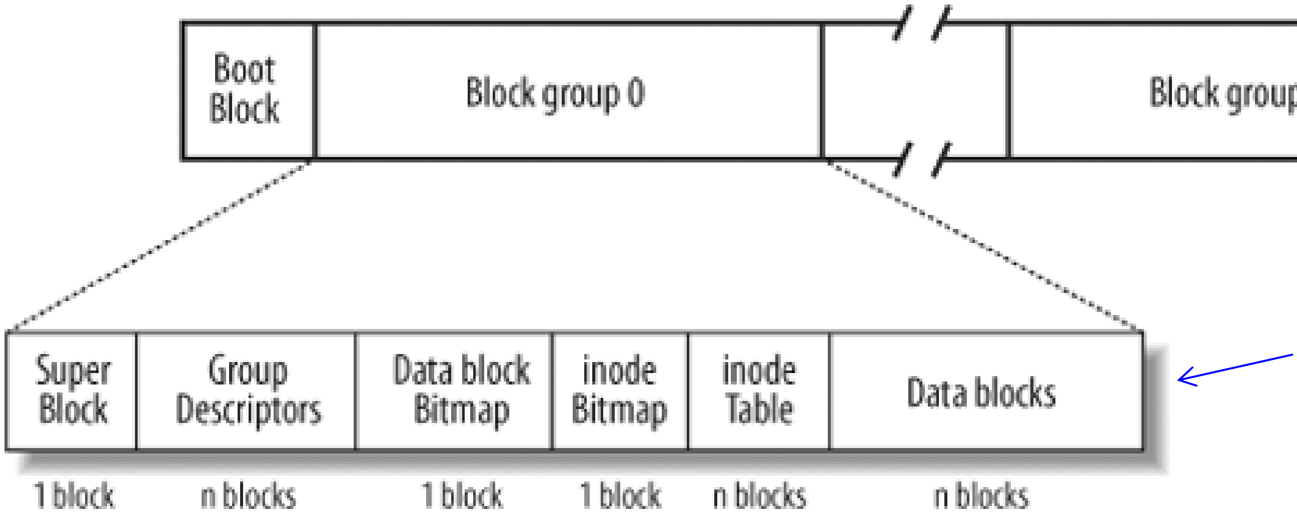
ext2

Disk Blocks

- Allocation of disk space to files is done with blocks.
- Choice of block size is fundamental
  - Block size small: Needs to store much location information
  - Block size large: Disk capacity wasted in partially used blocks (at the end of file – internal fragmentation)
- Typical Unix block sizes are 4KB and 8KB

Disk layout

- **Super block**: Filesystem-wide info (replicated a lot)
- **Group descriptors**: addresses of the other parts, etc.
- **Data block bitmap**: which blocks are free?
- **Inode bitmap**: which inodes are free?
- **Inode table**: the inodes themselves
- **Data blocks**: actual file data blocks



Original UNIX filesystem basically had one of this for the whole disk, which meant that metadata was always really far from data. This more modern "block group" idea drastically reduces the average distance between the two.

From "Understanding the Linux Kernel, 3e" by Marco Cesati, Daniel P. Bovet.

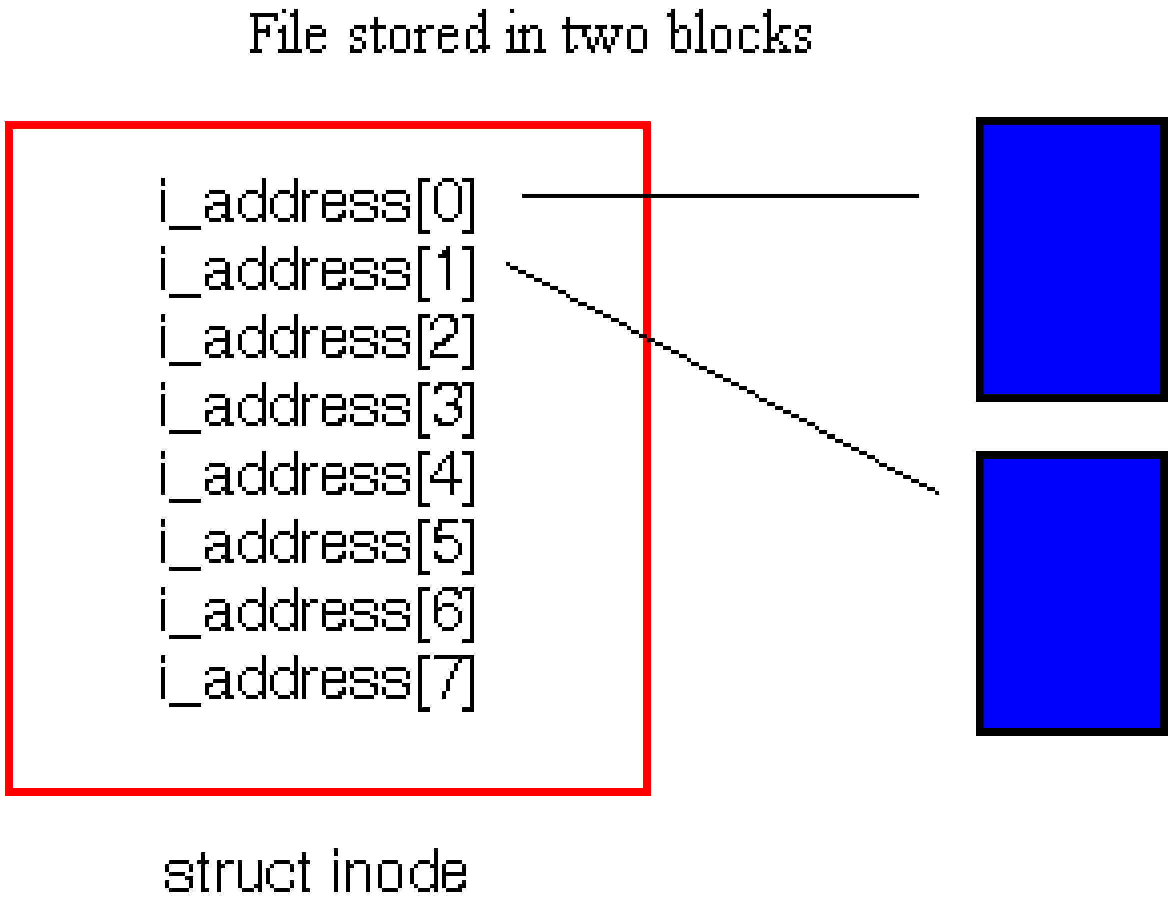
Inodes

- Inodes are fixed sized metadata describing the layout of a file
- Inode structure:
  - i_mode (directory IFDIR, block special file (IFBLK), character special file (IFCHR), or regular file (IFREG)
  - i_nlink
  - i_address[] (an array that holds addresses of blocks)
  - i_size (file size in bytes)
  - i_uid (user id)
  - i_gid (group id)
  - i_mtime (modification time & date)
  - i_atime (access time & date)

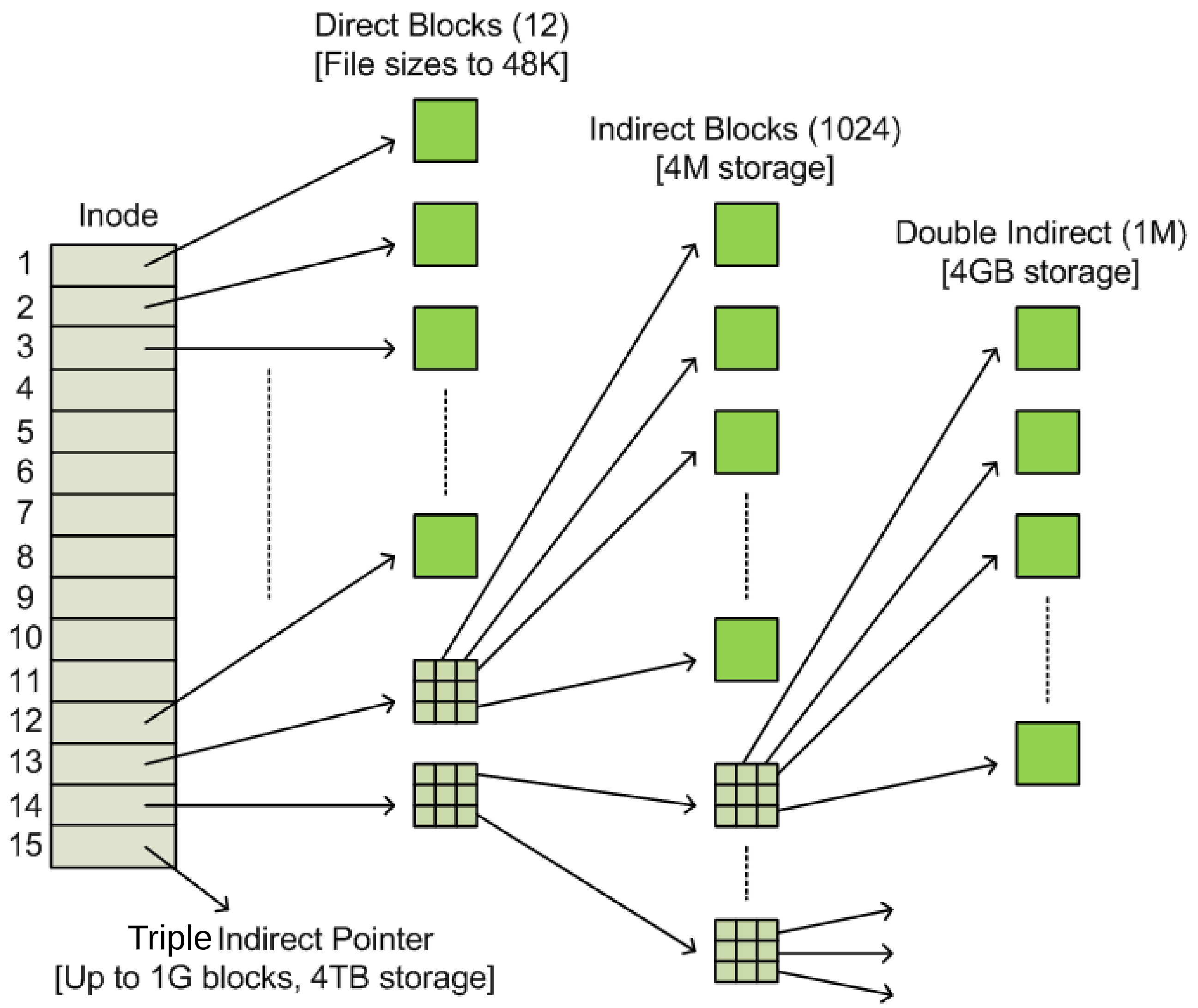
Inodes

- Metadata in Inode is space-limited
  - Limited NUMBER of inodes:
    - Inode storing region of disk is fixed when the file system is created
    - Run out of inodes -> can’t store more files ->
      Can get “out of disk” error even when capacity is available
  - Limited SIZE of inode:
    - Number of block addresses in a single inode only suffices for small files
    - Use (single and double) indirect inodes to find space for all blocks in a file

Inode indirection



Inode indirection



From “File Systems Indirect Blocks and Extents” by Cory Xie (link)

Directories and hard links

- Directories are special files that list file names and inode numbers
  (and some other minor metadata)

- What if two entries refer to the same inode number?
  - Two "files" that are actually the same content
  - This is called a **hard link**
  - Need to track "number of links" – deallocate inode when zero
  - This is an early example of filesystem-based storage efficiency:
    - Can store same data "twice" without actually storing more data!
    - Example: "Rsnapshot" tool can create multiple point-in-time backups while eliminating redundancy in unchanged files
    - *We'll see more advanced forms of filesystem-based storage efficiency later on!*

Soft links

- **Soft link**: an additional file/directory name.
  - Also called **symbolic link** or **symlink**.
  - A special file whose **contents** is the **path** to another file/directory.
  - Path can be relative or absolute
  - Can traverse file systems
  - Can point to nonexistent things
- Can be used as file system organization "duct tape"
  - Organize lots of file systems in one place (e.g., cheap NAS namespace virtualization)
  - Symlink a long, complex path to a simpler place, e.g.:

```
$ ln -s /remote/codebase/projectX/beta/current/build ~/mybuild
$ cd ~/mybuild
```

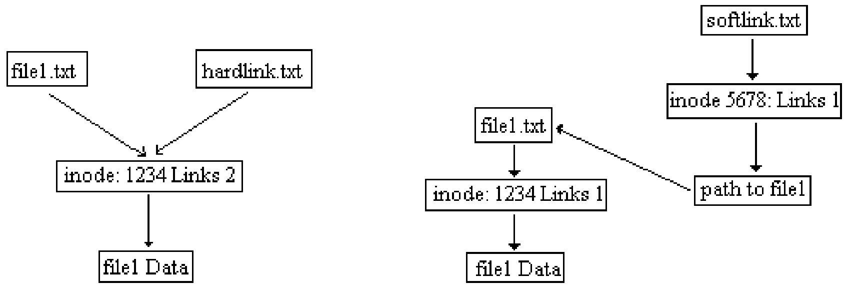


Figure from "Computer Forensics: Unix File Systems" by Thomas Schwarz (Santa Clara Univ)

EXT Allocation Algorithms

- Allocation – selecting block group:
  - Non-directories are allocated in the same block group as parent directory, if possible.
  - Directory entries are put into underutilized groups.
- Deallocation - deleted files have their inode link value decremented.
  - If the link value is zero, then it is unallocated.

EXT Details: Two time issues

- Time Values
  - Are stored as seconds since January 1, 1970, Universal Standard Time
  - Stored as 32-bit integer in most implementations
  - Remember Y2k? Get ready for the Year 2038 problem.
- Linux updates (in general)
  - A-time, when the content of file / directory is read.
  - This can be very bad: every read implies a write!!
  - Can be disabled: “noatime” option (atime field becomes useless)
  - Can be mitigated: “relatime” option – only update atime if file modified since current atime or if atime difference is large

Problems with ext2

- We solved the scalability/efficiency problem from FAT

- We still have one big problem left:

  Consistency: What happens when system crashes/fails during a write? Nothing good...

Journaling:
ext3, NTFS, and others

Why Journaling?

- Problem: Data can be inconsistent on disk
  - Writes can be committed out of order
  - Multiple writes to disk need to all occur and "match" (e.g. metadata of file size, inode listing of disk blocks, actual data blocks)
  - After a crash, need to walk *entire filesystem* to see if anything is inconsistent ("scandisk" or "chkdsk" in Windows, "fsck" in Linux)!
  - Uh oh! Drives are getting bigger more than they're getting faster!
    - Full checks could take DAYS on big arrays!! ☹

- How to solve?
  - Write our *intent* to disk ahead of the actual writes
  - These "intent" writes can be fast, as they can be ganged together (few seeks)
  - This is called **journaling**

Design questions

- Where is journal?
  - Same drive, separate drive/array, battery backed RAM, etc.
- What to journal?
  - Logical journal
    - Metadata journaling: Only log meta data in advance
  - Physical journal
    - Data journaling: Log advanced copy of the data
      (All data written twice!)
- What are the tradeoffs?
  - Costs vs. benefits

From “Journaling Filesystems” by Vince Freeh (NCSU)

Journaling

- Process:
  - record changes to cached metadata blocks in journal
  - periodically write the journal to disk
  - on-disk journal records changes in metadata blocks that have not yet themselves been written to disk
- Recovery:
  - apply to disk changes recorded in on-disk journal
  - resume use of file system
- On-disk journal: two choices
  - maintained on same file system as metadata, OR
  - stored on separate, stand-alone file system

Journaling Transaction Structure

- A journal transaction
  - consists of all metadata updates related to a single operation
  - transaction order must obey constraints implied by operations
  - the memory journal is a single, merged transaction

- Examples
  - Creating a file
    - creating a directory entry (modifying a directory block),
    - allocating an inode (modifying the inode bitmap),
    - initializing the inode (modifying an inode block)
  - Writing to a file
    - updating the file's write timestamp (modifying an inode block)
    - may also cause changes to inode mapping information and block bitmap if new data blocks are allocated

Journaling in Linux (ext3)

- Given the (merged) transaction from memory
- Start flushing the transaction to disk
  - Full metadata block is written to journal
  - Descriptor blocks are written that give the home disk location for each metadata block
- Wait for all outstanding filesystem operations in this transaction to complete
- Wait for all outstanding transaction updates to be complete
- Update the journal header blocks to record the new head/tail
- When all metadata blocks have been written to their home disk location, write a new set of journal header blocks to free the journal space occupied by the (now completed) transaction

Journaling modes (ext3)

- Nomenclature for ext3 journaling:
  - Journal **write**: write the intended changes
  - Journal **commit**: marks end of journal entry; indicates a promise that all changes are either reflected in the fixed-block filesystem *or* recoverable if there's an outage
    ("I promise the data is either stored or restorable")

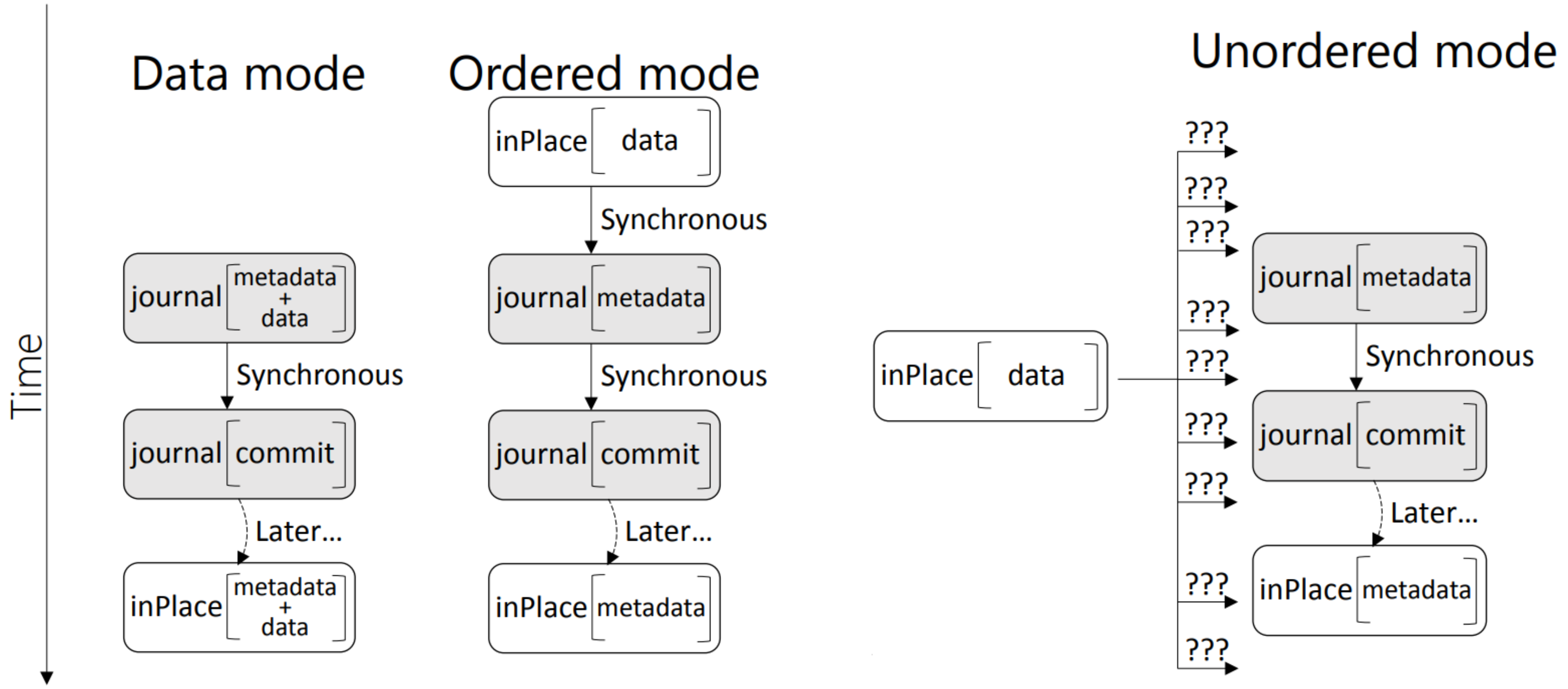
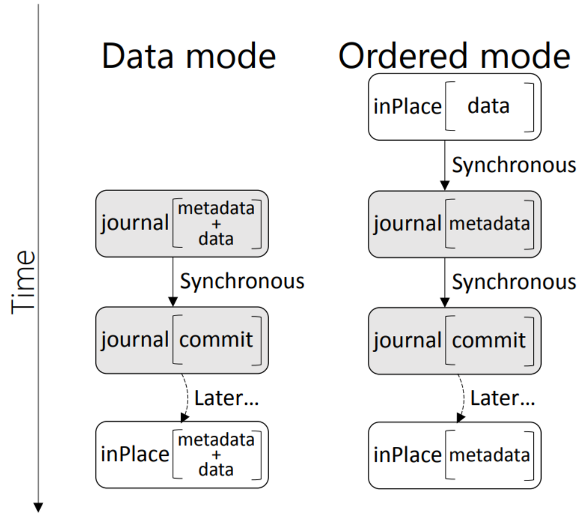
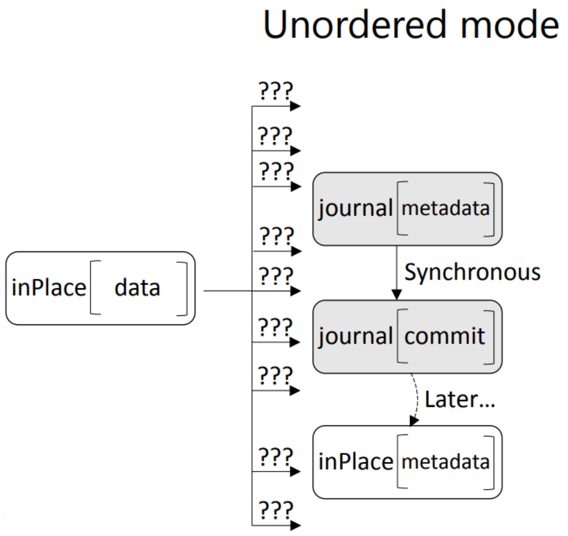


Figure from CS 161 lecture "Journaling" by James Mickens, Harvard

Journaling with ext3: Data mode

- Data mode
  - ☺ Post-crash data is guaranteed perfect
  - ☹ Double-write
- Ordered mode
  - ☺ No double-write of data
  - ☹ Can lose mid-crash appends
- Unordered mode
  - ☺ Best performance
  - ☹ Post-crash, files may contain "junk" if metadata written before data





Based on CS 161 lecture "Journaling" by James Mickens, Harvard

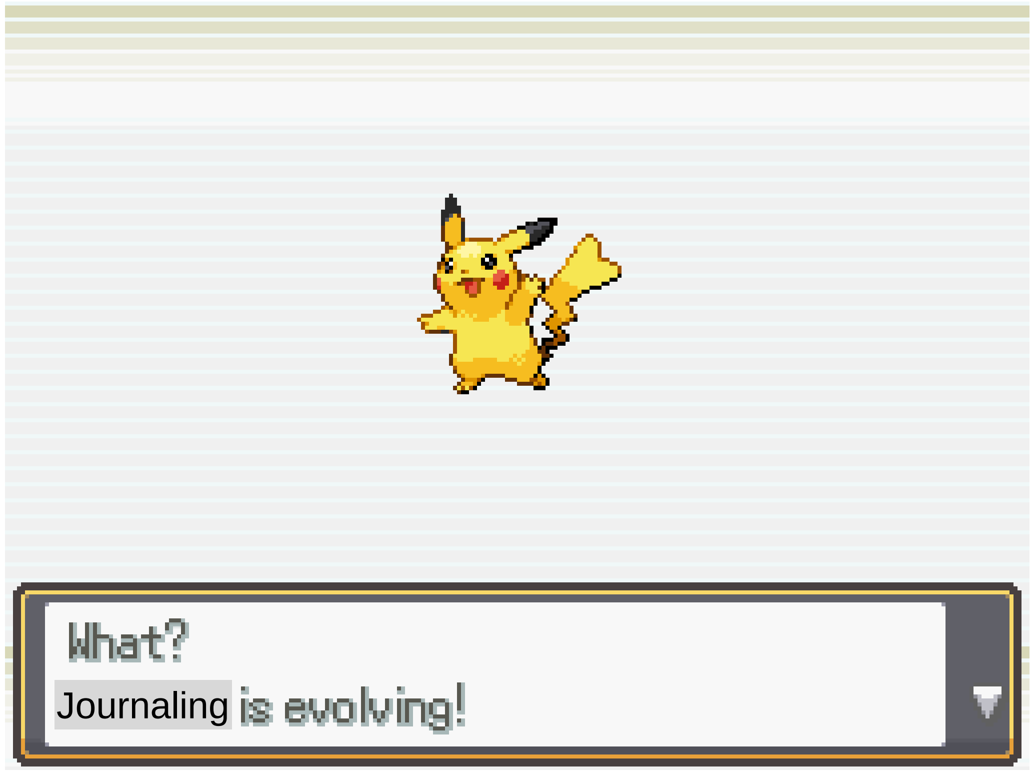
Who does journaling?

- Everyone does journaling.
  - Microsoft Windows: NTFS
  - Linux: ext3, ext4, jfs, reiserfs
  - Apple OSX: HFS+

- Full list:
  - OCFS, OCFS2, XFS, JFS, QFS, Be File, NSS, NWFS, ODS-2, ODS-5, UDF, VxFS, Fossil, ZFS, VMFS2, VMFS3, Btrfs, GFS, GPFS, HPFS, NTFS, HFS, HFS Plusline, FFS, UFS1, UFS2, LFS, ext2, ext3, ext4, Lustre, NILFS, ReiserFS, Reiser4

Can we go further?

- If journaling is so great, what if we just NEVER wrote to fixed blocks, and used the journal for EVERYTHING????



Can we go further?

- Yes!

Log-structured file systems

Based on “Log-Structured File Systems” by Emin Gun Sirer and Michael D. George (Cornell)

Basic Problem

- Most file systems now have large memory caches (buffers) to hold recently-accessed blocks
  - Most reads are satisfied from the buffer cache
- From the point of view of the disk, most traffic is write traffic
  - To speed up disk I/O, we need to make writes go faster
  - *NOTE: This assumption depends strongly on workload!*
- Disk performance is ultimately limited by seek delay
  - With current file systems, adding a block takes several writes (to the file and to the metadata), requiring several disk seeks
  - So...let's not do that.

M. Rosenblum and J. K. Ousterhout. The design and implementation of a Log-structured File system. ACM TOCS, 10(1):26–52, 1992.

LFS: Basic Idea

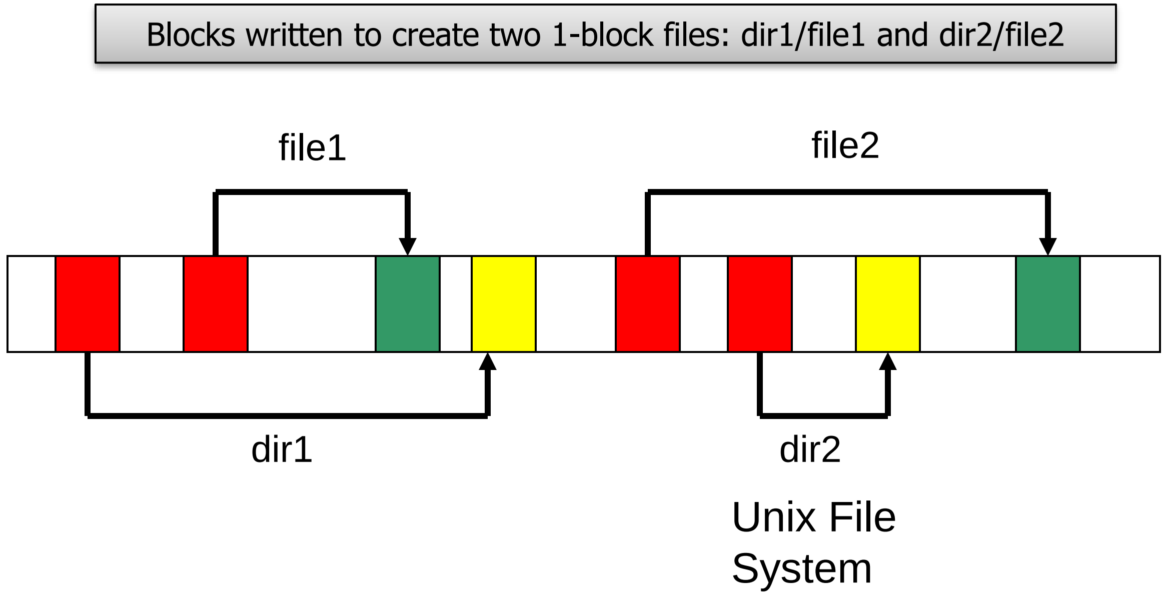
- An alternative is to use the disk as a ***log***
  - Log: a data structure that is written only at the head
- If the disk is managed as a log, there'd be *no* head seeks!
  - The log is always added to sequentially
- New data and metadata (inodes, directories) are accumulated in the buffer cache, then written all at once in large blocks (e.g., segments of 0.5M or 1M)
  - This would greatly increase disk throughput!

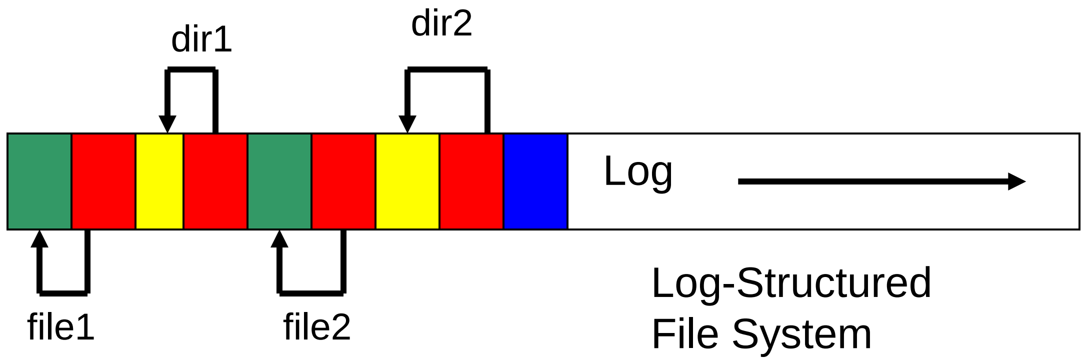
- How does this really work? How do we read? What does the disk structure look like? etc.?

LFS Data Structures

- **Segments**: log containing data blocks and metadata
- **inodes**: as in Unix, inodes contain physical block pointers for files
- **inode map**: a table indicating where each inode is on the disk
  - inode map blocks are written as part of the segment; a table in a fixed checkpoint region on disk points to those blocks
- **segment summary**: info on every block in a segment
- **segment usage table**: info on the amount of “live” data in a block

LFS vs. traditional FS


Blocks written to create two 1-block files: dir1/file1 and dir2/file2
file1
file2
dir1
dir2
Unix File System



🟥	inode
🟨	directory
🟩	data
🟦	inode map

From “Log-Structured File Systems” by Emin Gun Sirer and Michael D. George (Cornell)

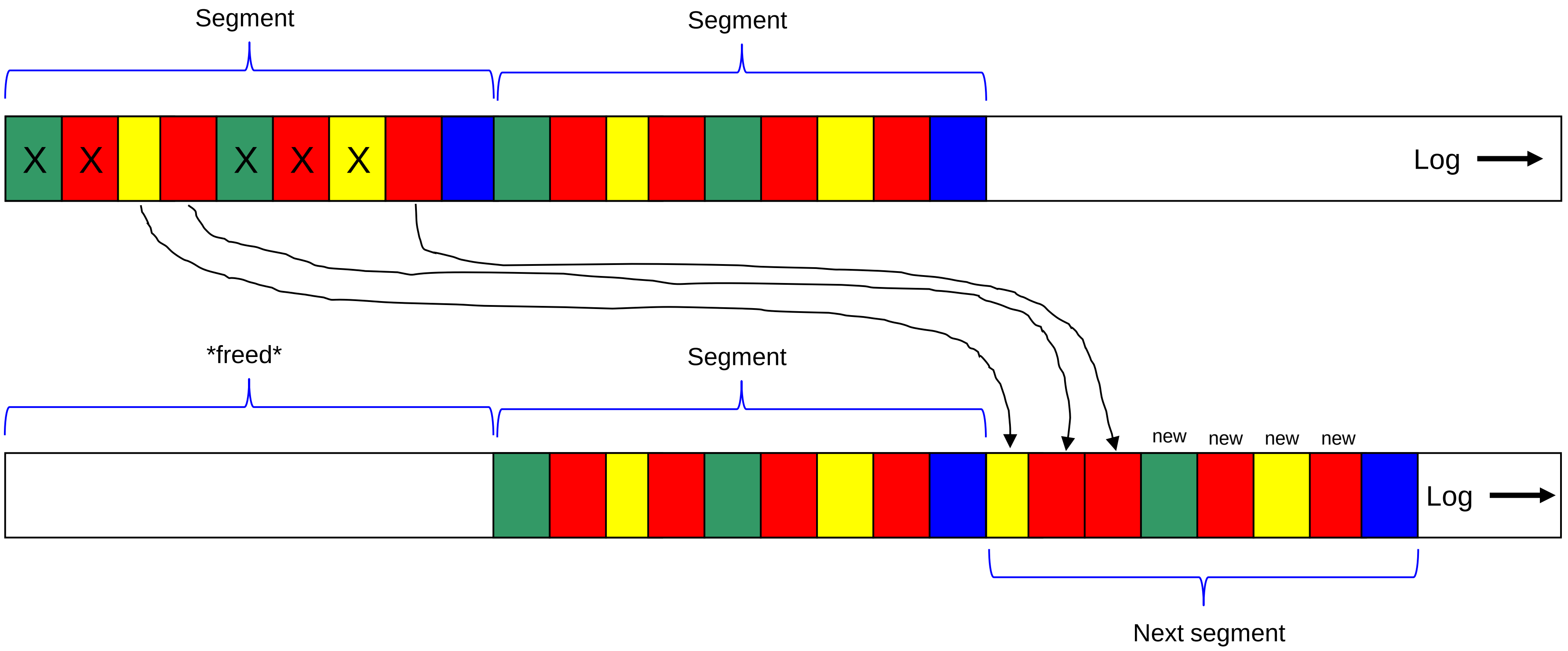
LFS: read and write

- Every write causes new blocks to be added to the current segment buffer in memory; when that segment is full, it is written to the disk
- Reads are no different than in Unix File System, once we find the inode for a file (in LFS, using the inode map, which is cached in memory)
- Over time, segments in the log become fragmented as we replace old blocks of files with new block
- Problem: in steady state, we need to have contiguous free space in which to write

Cleaning

- The major problem for a LFS is *cleaning*, i.e., producing contiguous free space on disk
- A cleaner process "cleans" old segments, i.e., takes several non-full segments and compacts them, creating one full segment, plus free space
- The cleaner chooses segments on disk based on:
  - **utilization**: how much is to be gained by cleaning them
  - **age**: how likely is the segment to change soon anyway
- Cleaner cleans "cold" segments at 75% utilization and "hot" segments at 15% utilization (because it's worth waiting on "hot" segments for blocks to be rewritten by current activity)

LFS cleaning



X = superceded in later segment

🟥	inode
🟨	directory
🟩	data
🟦	inode map

LFS Failure Recovery

- Checkpoint and roll-forward
- Recovery is very fast
  - No fsck, no need to check the entire disk
  - Recover the last checkpoint, and see how much data written after the checkpoint you can recover
  - Some data written after a checkpoint may be lost
  - Seconds versus hours

LFS Summary

- Basic idea is to handle reads through caching and writes by appending large segments to a log
- Greatly increases disk performance on writes, file creates, deletes, ….
- Reads that are not handled by buffer cache are same performance as normal file system (except locality is busted)
- Requires cleaning daemon to produce clean space, which takes additional CPU time

Use of log-structured filesystems

- In the role of a traditional filesystem – not a lot:
  - Original Ousterhout & Rosemblum LFS in Sprite OS (1992)
  - Various academic projects, some small commercial ventures
  - The NetApp “Write Anywhere File Layout (WAFL)” (we’ll cover this one next)

- Specific to flash or optical media – more common (recall that those mediums have trouble with in-place writes):
  - UDF (commonly used on CD/DVD)
  - JFFS, JFFS2 (commonly used in for flash in embedded Linux systems)
  - Others (mostly focused around flash)

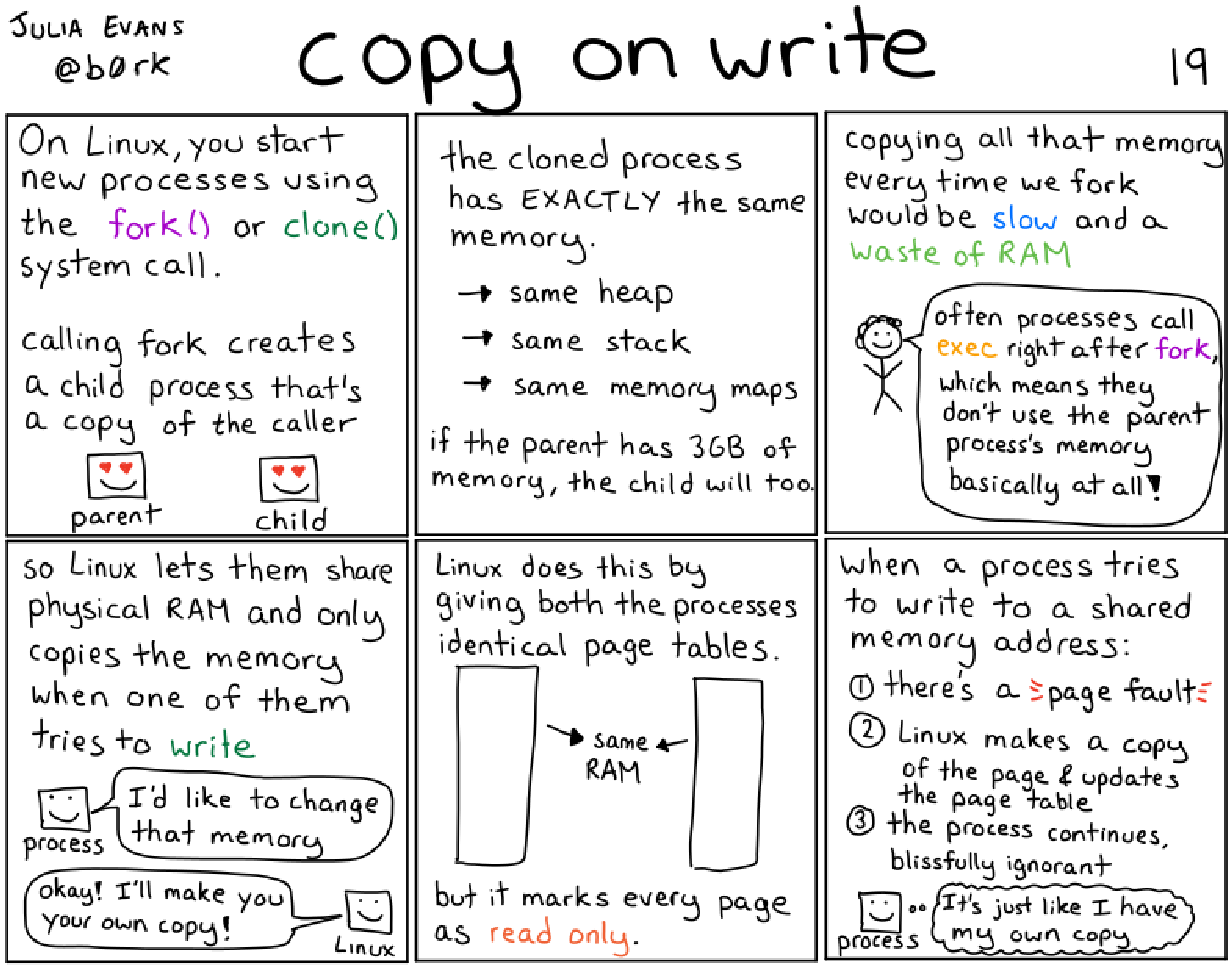
Note: “flash” above means raw flash, not SSDs – the data-hiding, wear-leveling, etc. done by SSDs obviates many of the benefits

Remaining problem

- We’ve solved performance/efficiency issues with inodes and chunks (ext2)
- We’ve solved consistency with journaling (and perhaps logging)
- Remaining problem:
  - **Lack of magical superpowers that make you millions of dollars**

Highly indirected filesystems

First, a sidebar: Copy on Write



Julia Evans
@b0rk

copy on write

19

On Linux, you start new processes using the fork() or clone() system call.

calling fork creates a child process that's a copy of the caller

the cloned process has EXACTLY the same memory.

→ same heap
→ same stack
→ same memory maps

if the parent has 3GB of memory, the child will too.

copying all that memory every time we fork would be slow and a waste of RAM

often processes call exec right after fork, which means they don't use the parent process's memory basically at all!

so Linux lets them share physical RAM and only copies the memory when one of them tries to write

process
I'd like to change that memory
okay! I'll make you your own copy!
Linux

Linux does this by giving both the processes identical page tables.

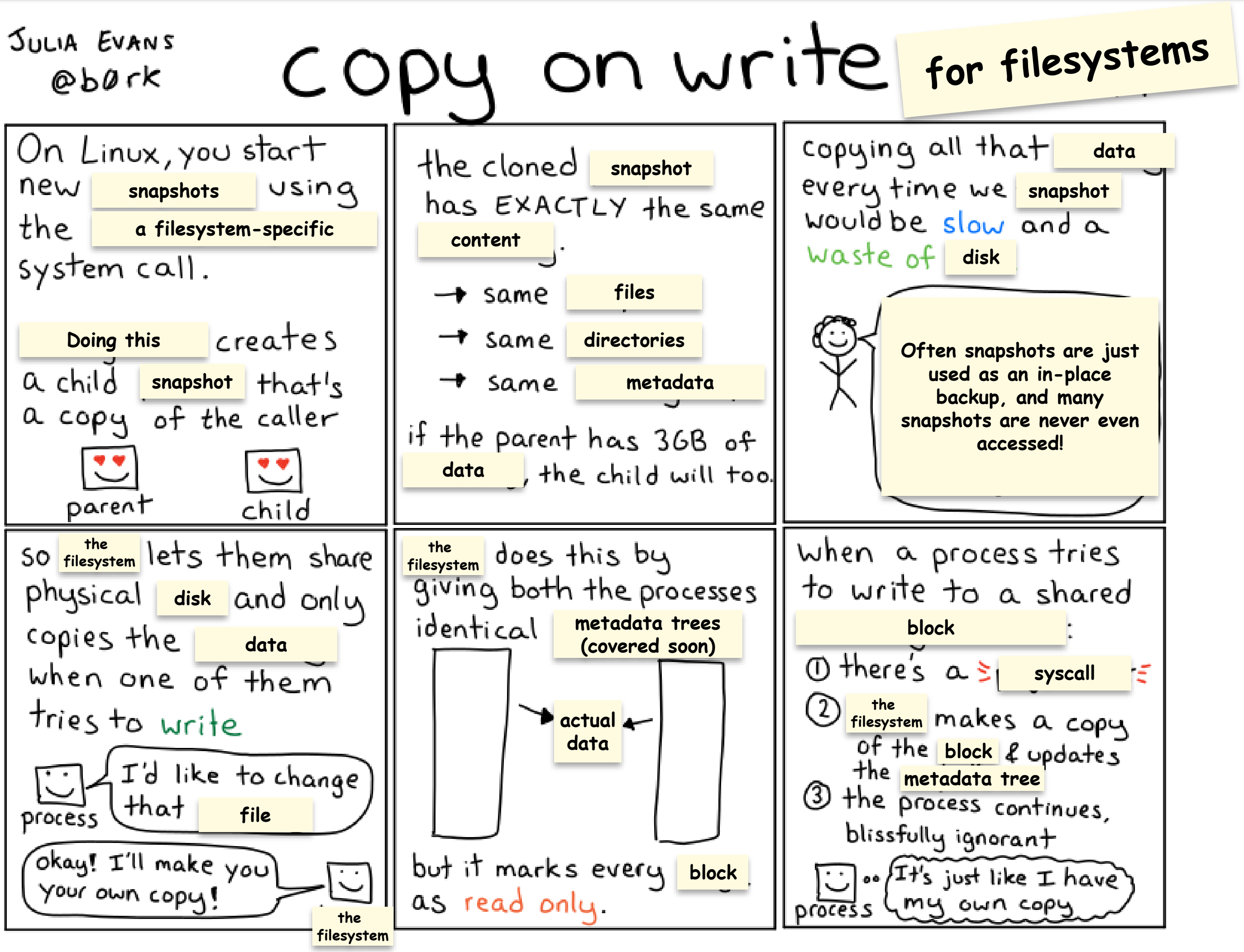
but it marks every page as read only.

when a process tries to write to a shared memory address:

① there's a page fault
② Linux makes a copy of the page & updates the page table
③ the process continues, blissfully ignorant

Source

Snapshots and clones: Adapting this story to entire filesystems



JULIA EVANS @b0rk

copy on write for filesystems

On Linux, you start new snapshots using the a filesystem-specific system call.

Doing this creates a child snapshot that's a copy of the caller

the cloned snapshot has EXACTLY the same content.

→ same files
→ same directories
→ same metadata

if the parent has 3GB of data, the child will too.

copying all that data every time we snapshot would be slow and a waste of disk

Often snapshots are just used as an in-place backup, and many snapshots are never even accessed!

so the filesystem lets them share physical disk and only copies the data when one of them tries to write

process
I'd like to change that file
okay! I'll make you your own copy!
the filesystem

the filesystem does this by giving both the processes identical metadata trees (covered soon)

but it marks every block as read only.

when a process tries to write to a shared block:

① there's a syscall

② the filesystem makes a copy of the block & updates the metadata tree

③ the process continues, blissfully ignorant

Source

Desires

- We want **snapshots**: point-in-time read-only replicas of current data which can be taken in O(1) time and space

- We want **clones**: point-in-time writable replicas of current data which can be taken in O(1) time and space, and we only store changes between clone and original

- We want various other features, like:
  - Directory-level **quotas** (capacity limits),
  - **Deduplication** (identify redundant data and store it just once), and
  - **Thin-provisioning** (provide storage volumes with a total capacity greater than actual disk storage available)

Write Anywhere File Layout (WAFL)

- Inspired ZFS, HAMMER, btrfs
- Core Idea: Write whole **snapshots** to disk (read only views of the whole filesystem)
  - Snapshots are virtually free: use **copy-on-write** to preserve them
  - Can be taken automatically on a schedule
- Uses:
  - Users can recover accidentally deleted files
  - Sys admins can create backups from running system
  - System can restart quickly after unclean shutdown (roll back to last automatic snapshot)
- Snapshots accessible from .snapshot directory in root

```
spike% ls -lut .snapshot/*/todo
-rw-r--r-- 1 hitz  52880 Oct 15 00:00
.snapshot/nightly.0/todo
-rw-r--r-- 1 hitz  52880 Oct 14 19:00
.snapshot/hourly.0/todo
-rw-r--r-- 1 hitz  52829 Oct 14 15:00
.snapshot/hourly.1/todo
```

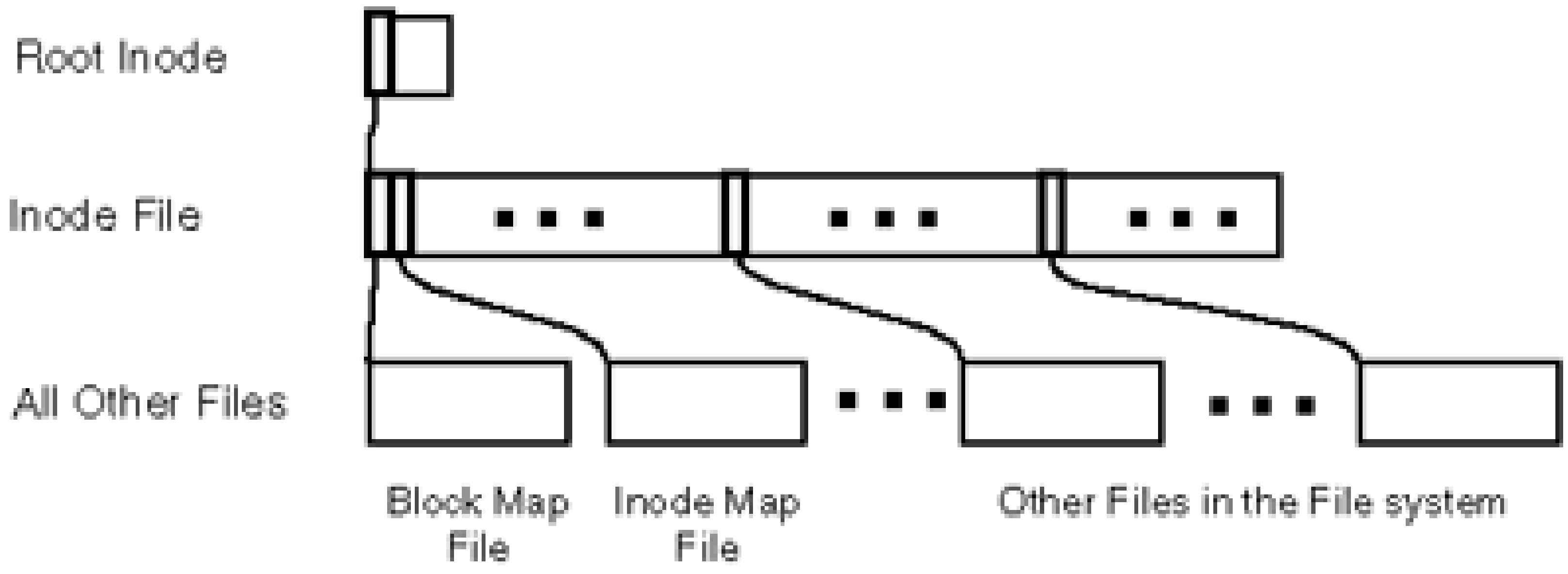
WAFL File Descriptors

- Inode based system with 4 KB blocks
- Inode has 16 pointers, which vary in type depending upon file size
  - For files smaller than 64 KB:
    - Each pointer points to data block
  - For files larger than 64 KB:
    - Each pointer points to indirect block
  - For really large files:
    - Each pointer points to doubly-indirect block
- For very small files (less than 64 bytes), data kept in inode itself, instead of using pointers to blocks

Adapted from "File System Design for an NFS File Server Appliance" by Dave Hitz, et al. Original slides appear later in this deck.

WAFL Meta-Data

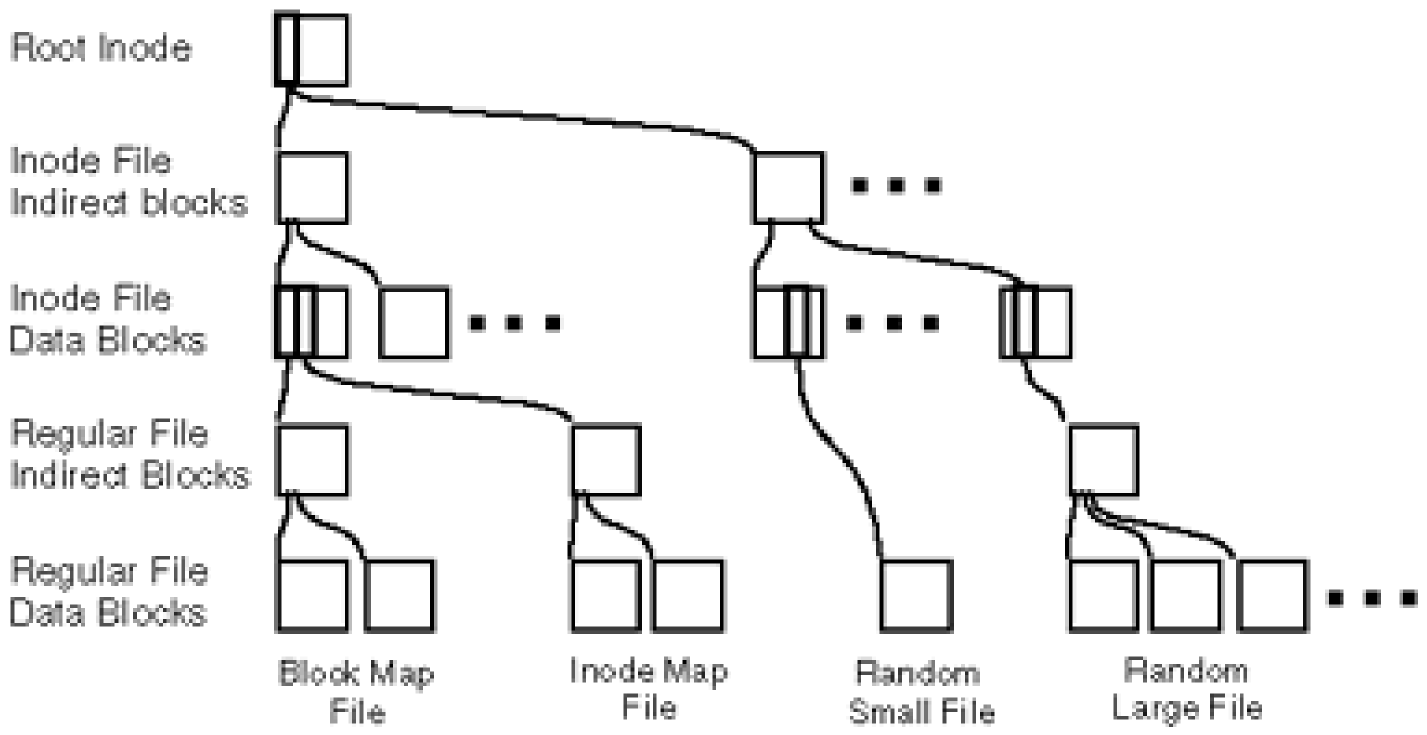
- **Key insight:** Meta-data stored in **files**!
  - Inode *file* – stores inodes
  - Block-map *file* – stores free blocks
  - Inode-map *file* – identifies free inodes



Adapted from "File System Design for an NFS File Server Appliance" by Dave Hitz, et al. Original slides appear later in this deck.

Zoom of WAFL Meta-Data (Tree of Blocks)

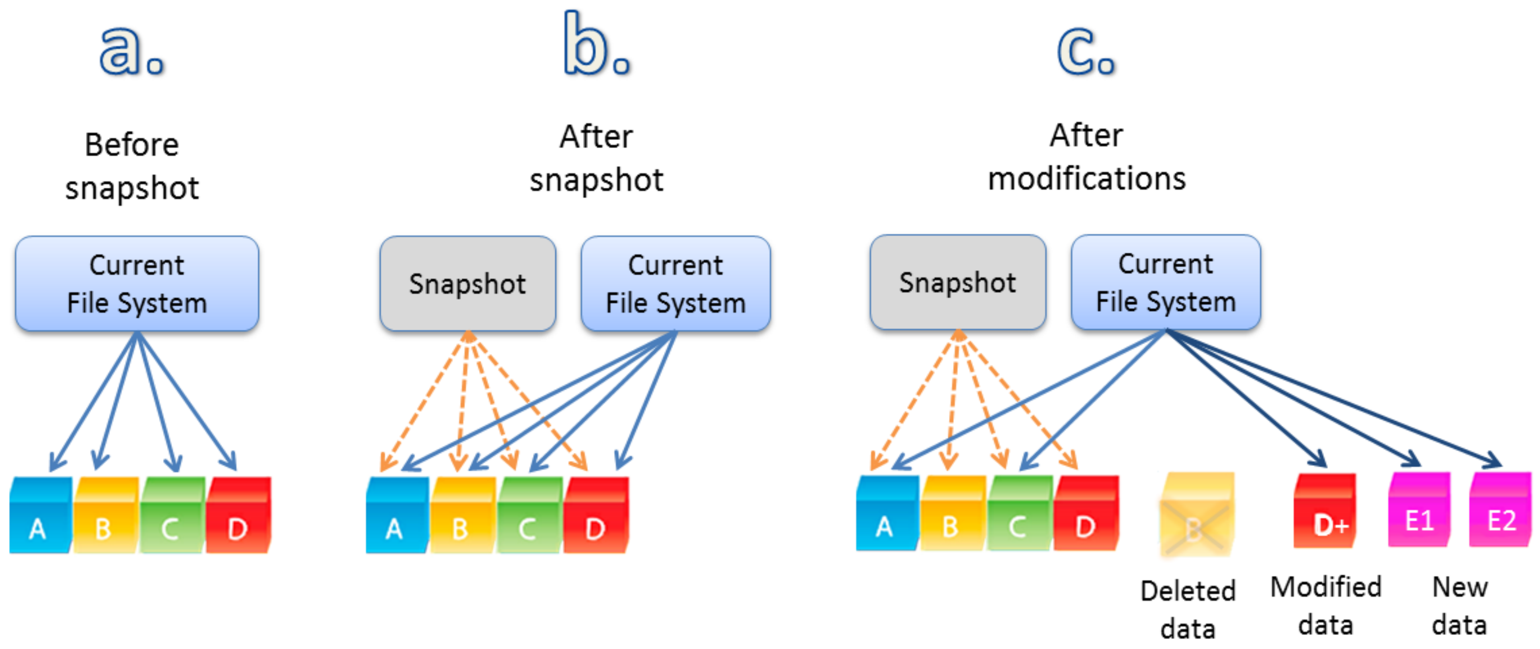
- Root inode must be in fixed location
- Other blocks can be written anywhere



Adapted from "File System Design for an NFS File Server Appliance" by Dave Hitz, et al. Original slides appear later in this deck.

Snapshots (1 of 2)

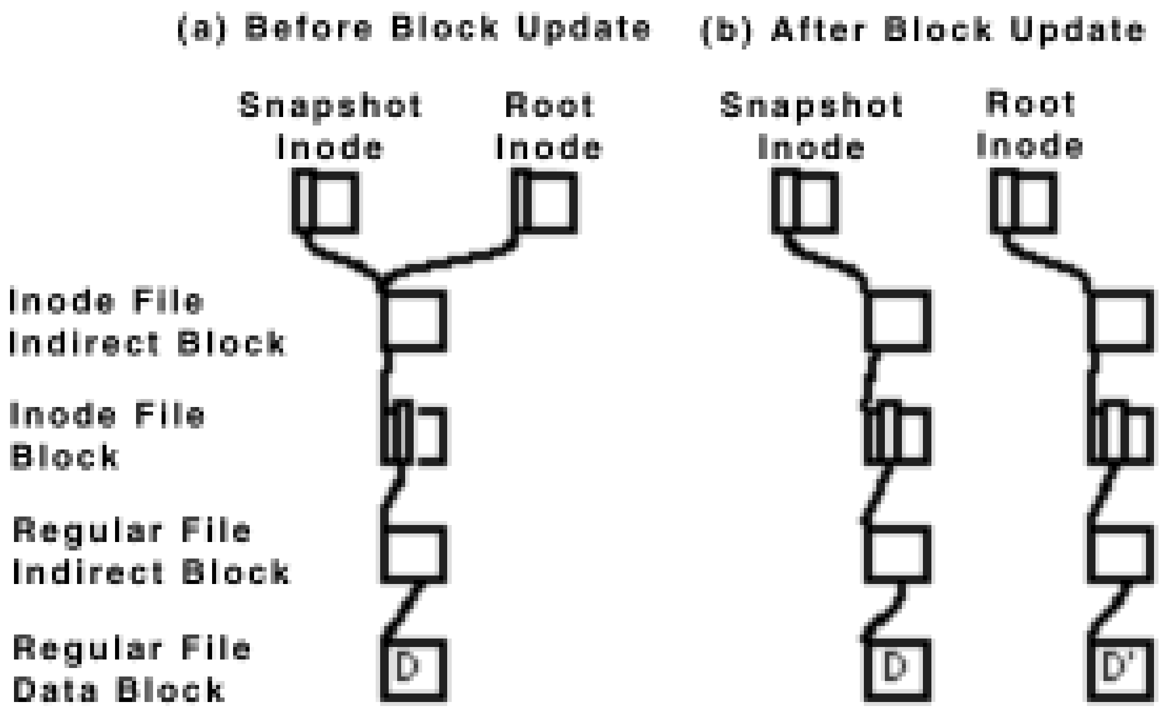
- To take a snapshot: **Copy root inode only**, do copy-on-write for changed data blocks



- Over time, old snapshot references more and more data blocks that are not used
- Rate of file change determines how many snapshots can be stored on system

Snapshots (2 of 2)

- When disk block modified, must modify meta-data (indirect pointers) as well



- Batch, to improve I/O performance

Consistency Points

- Make restart quick (like journaling): creates special snapshot called **consistency point** every few seconds
- Batched operations are written to disk each consistency point
  - Like a **log structured filesystem!**
- In between consistency points, data only written to RAM
  - But it's battery-backed **Non-Volatile RAM (NVRAM)!**
  - Recover after outage by just reverting to last consistency point, then replay NVRAM

Adapted from "File System Design for an NFS File Server Appliance" by Dave Hitz, et al. Original slides appear later in this deck.

Later NetApp/WAFL capabilities

- What if we make a big file on a WAFL file system, then treat that file as a virtual block device, and we make a WAFL file system on that?
  - Now file systems can dynamically grow and shrink (because they're really files)
  - Can do some optimizations to reduce the overhead of going through two file system layers: inner file system can be "aware" that it's hosted on an outer file system
  - Result: **thin provisioning** – Allocate more storage than you've got

- Similarly, LUNs are just fixed-size files
  - Result: **SAN support**

- Multiple files can refer to same data blocks with copy-on-write semantics
  - Result: **writable clones**

ZFS

- Copy-on-Write functions similar to WAFL
  - Similar enough that NetApp sued Sun over it...
- Integrates Volume Manager & File System
  - Software RAID without the write hole
- Integrates File System & Buffer Management
  - Advanced prefetching: strided patterns etc.
  - Use Adaptive Replacement Cache (ARC) instead of LRU
- File System reliability
  - Check summing of all data and metadata
  - Redudant Metadata

Conclusion

- File system design is a major contributor to overall performance

- File system can provide major differentiating features
  - Do things that you didn’t know you wanted to do (snapshots, clones, etc.)

Questions?

WAFL: The history and details

A slightly updated version of a very early technical presentation made by the founders of NetApp

About the authors

- Dave Hitz, James Lau, and Michael Malcolm

- Founded NetApp in 1992
- NetApp is now a fortune 500 company worth $10 billion
- Malcolm left early, other two stuck around
- Current pics:

File System Design for an NFS File Server Appliance

Dave Hitz, James Lau, and Michael Malcolm

Technical Report TR3002

NetApp

2002

http://www.netapp.com/us/library/white-papers/wp_3002.html

(At WPI: http://www.wpi.edu/Academics/CCC/Help/Unix/snapshots.html)

Introduction

- In general, *appliance* is device designed to perform specific function
- Distributed systems trend has been to use appliances instead of general purpose computers. Examples:
  - *routers* from Cisco and Avici
  - network *terminals*
  - network *printers*
- For files, not just another computer with your files, but new type of network appliance

  → Network File System (NFS) file server

Introduction: NFS Appliance

- NFS File Server Appliances have different requirements than those of general purpose file system
  - NFS access patterns are different than local file access patterns
  - Large client-side caches result in fewer reads than writes
- Network Appliance Corporation uses Write Anywhere File Layout (WAFL) file system

Introduction: WAFL

- WAFL has 4 requirements
  - Fast NFS service
  - Support large file systems (10s of GB) that can grow (can add disks later)
  - Provide high performance writes and support Redundant Arrays of Inexpensive Disks (RAID)
  - Restart quickly, even after unclean shutdown
- NFS and RAID both strain write performance:
  - NFS server must respond after data is written
  - RAID must write parity bits also

Outline

- Introduction (done)
- Snapshots : User Level (next)
- WAFL Implementation
- Snapshots: System Level
- Performance
- Conclusions

Introduction to Snapshots

- *Snapshots* are copy of file system at given point in time
- WAFL creates and deletes snapshots automatically at preset times
  - Up to 255 snapshots stored at once
- Uses *copy-on-write* to avoid duplicating blocks in the active file system
- Snapshot uses:
  - Users can recover accidentally deleted files
  - Sys admins can create backups from running system
  - System can restart quickly after unclean shutdown
    - Roll back to previous snapshot

User Access to Snapshots

- Example, suppose accidentally removed file named "`todo`":

```
CCCWORK3% ls -lut .snapshot/*/todo
-rw-rw---- 1 claypool claypool 4319 Oct 24 18:42
.snapshot/2011_10_26_18.15.29/todo
-rw-rw---- 1 claypool claypool 4319 Oct 24 18:42
.snapshot/2011_10_26_19.27.40/todo
-rw-rw---- 1 claypool claypool 4319 Oct 24 18:42
.snapshot/2011_10_26_19.37.10/todo
```

- Can then recover most recent version:

```
CCCWORK3% cp .snapshot/2011_10_26_19.37.10/todo todo
```

- Note, snapshot directories (`.snapshot`) are hidden in that they don't show up with `ls` (even `ls -a`) unless specifically requested

Snapshot Administration

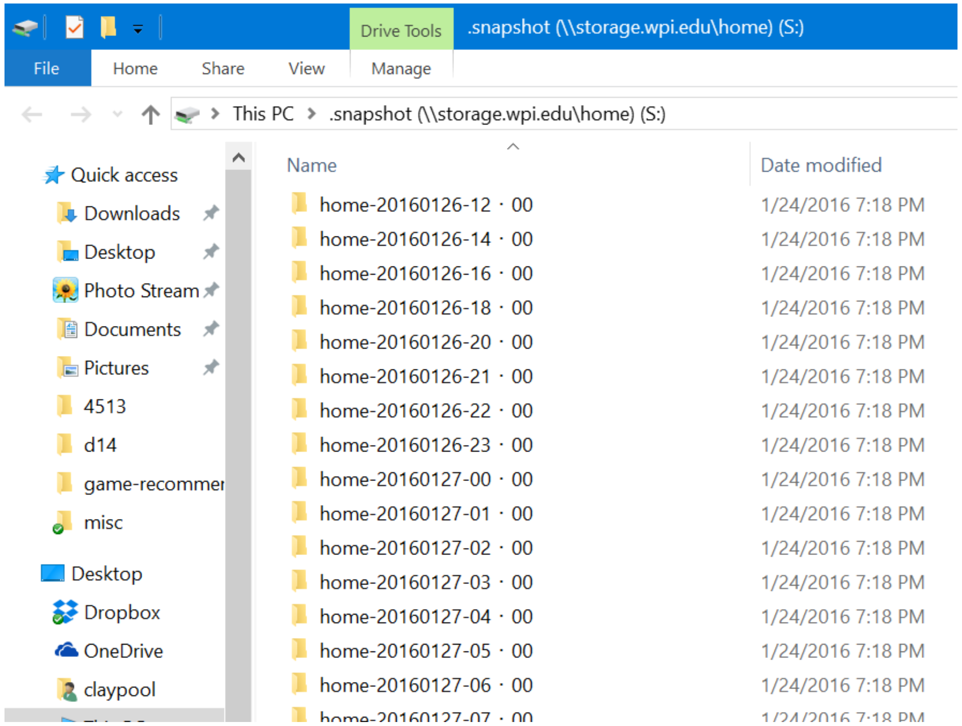
- WAFL server allows sys admins to create and delete snapshots, but usually automatic
- At WPI, snapshots of `/home`. Says:
  - 3am, 6am, 9am, noon, 3pm, 6pm, 9pm, midnight
  - Nightly snapshot at midnight every day
  - Weekly snapshot is made on Saturday at midnight every week

  → But looks like every 1 hour (fewer copies kept for older periods and 1 week ago max)

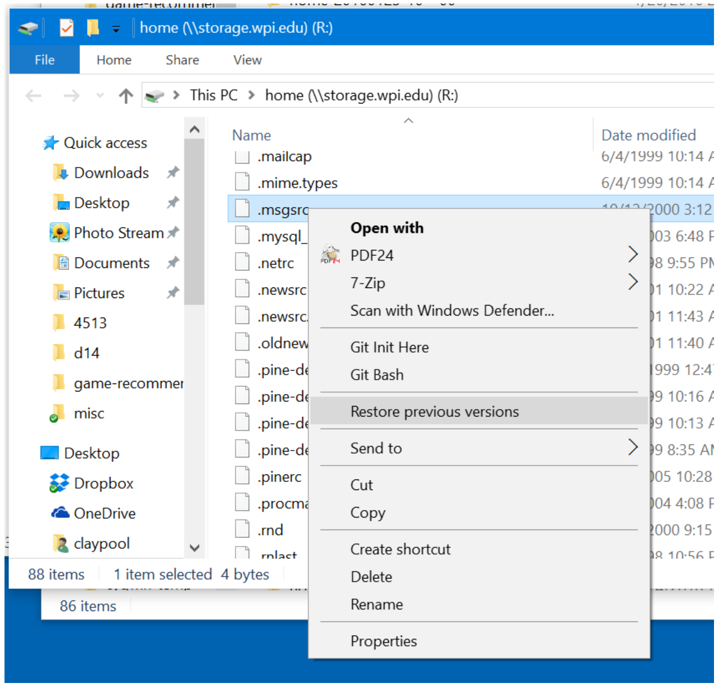
```
claypool 168 CCCWORK3% cd .snapshot
claypool 169 CCCWORK3% ls -1
home-20160121-00:00/
home-20160122-00:00/
home-20160122-22:00/
home-20160123-00:00/
home-20160123-02:00/
home-20160123-04:00/
home-20160123-06:00/
home-20160123-08:00/
home-20160123-10:00/
home-20160123-12:00/
…
home-20160127-16:00/
home-20160127-17:00/
home-20160127-18:00/
home-20160127-19:00/
home-20160127-20:00/
home-latest/
```

Snapshots at WPI (Windows)

- Mount UNIX space (`\\storage.wpi.edu\home`), add `\.snapshot` to end



Name	Date modified
home-20160126-12 · 00	1/24/2016 7:18 PM
home-20160126-14 · 00	1/24/2016 7:18 PM
home-20160126-16 · 00	1/24/2016 7:18 PM
home-20160126-18 · 00	1/24/2016 7:18 PM
home-20160126-20 · 00	1/24/2016 7:18 PM
home-20160126-21 · 00	1/24/2016 7:18 PM
home-20160126-22 · 00	1/24/2016 7:18 PM
home-20160126-23 · 00	1/24/2016 7:18 PM
home-20160127-00 · 00	1/24/2016 7:18 PM
home-20160127-01 · 00	1/24/2016 7:18 PM
home-20160127-02 · 00	1/24/2016 7:18 PM
home-20160127-03 · 00	1/24/2016 7:18 PM
home-20160127-04 · 00	1/24/2016 7:18 PM
home-20160127-05 · 00	1/24/2016 7:18 PM
home-20160127-06 · 00	1/24/2016 7:18 PM
home-20160127-07 · 00	1/24/2016 7:18 PM



Note, files in `.snapshot` do not count against quota

- Can also right-click on file and choose "restore previous version"

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WAFL File Descriptors

- Inode based system with 4 KB blocks
- Inode has 16 pointers, which vary in type depending upon file size
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  - For really large files:
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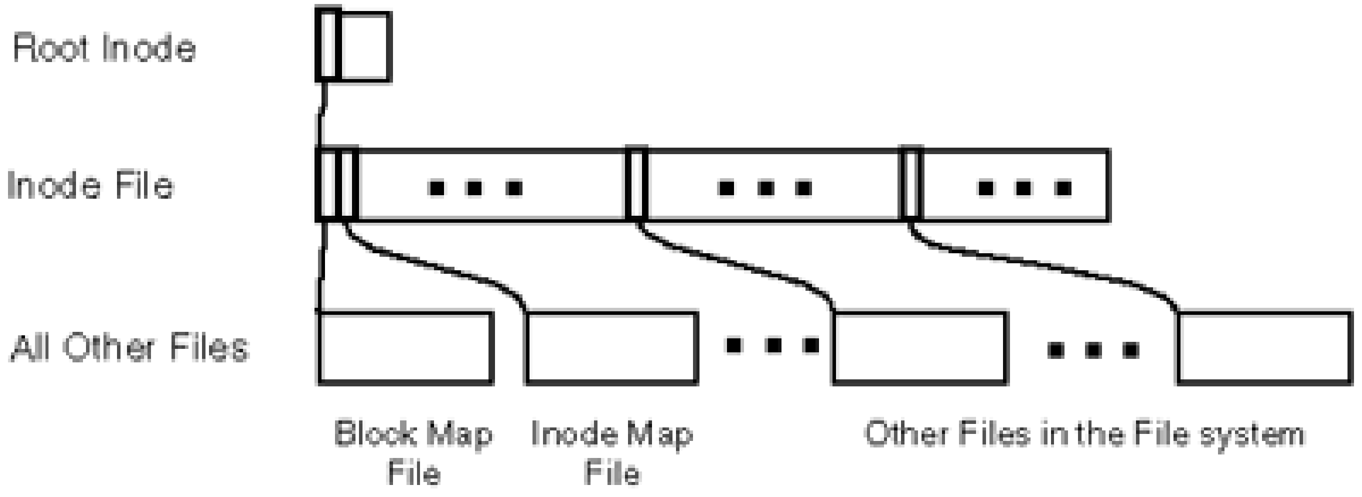
- For very small files (less than 64 bytes), data kept in inode itself, instead of using pointers to blocks

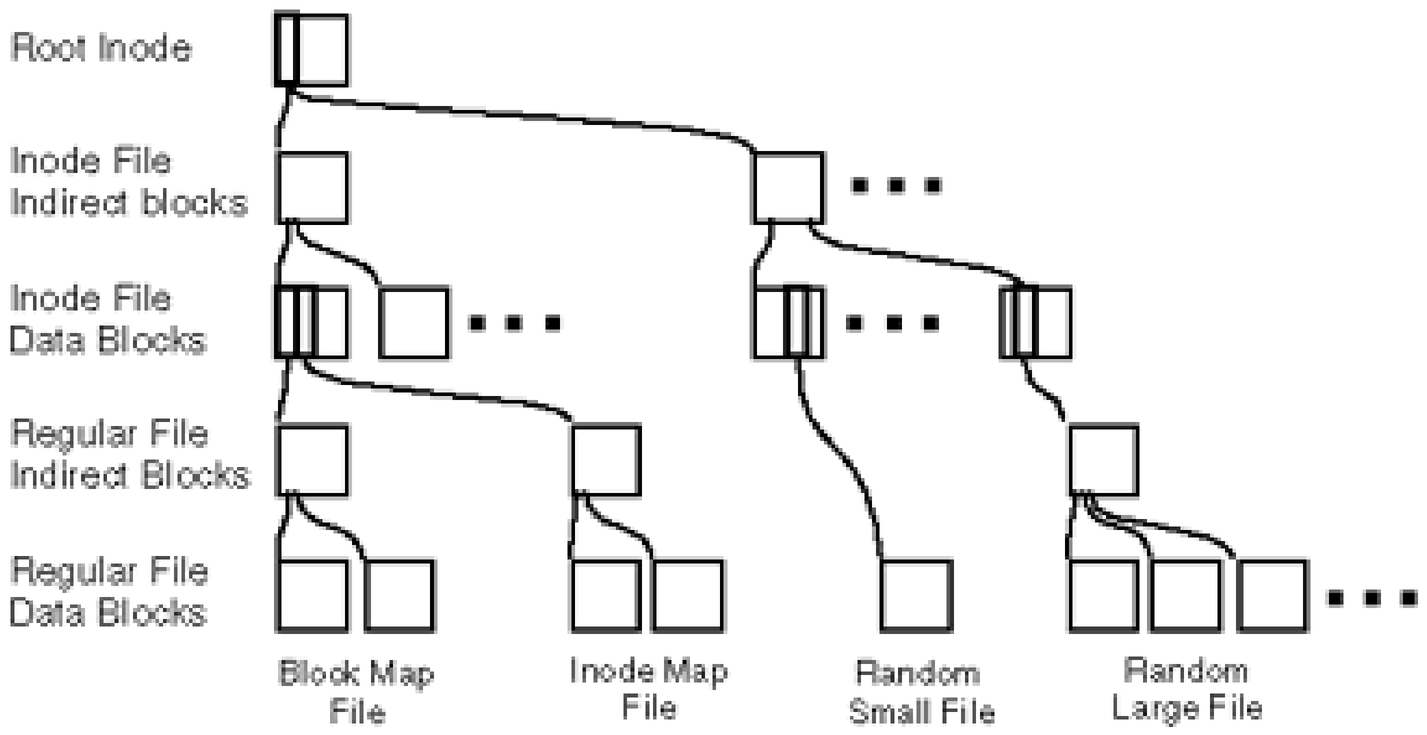
WAFL Meta-Data

- Meta-data stored in files
  - Inode file – stores inodes
  - Block-map file – stores free blocks
  - Inode-map file – identifies free inodes



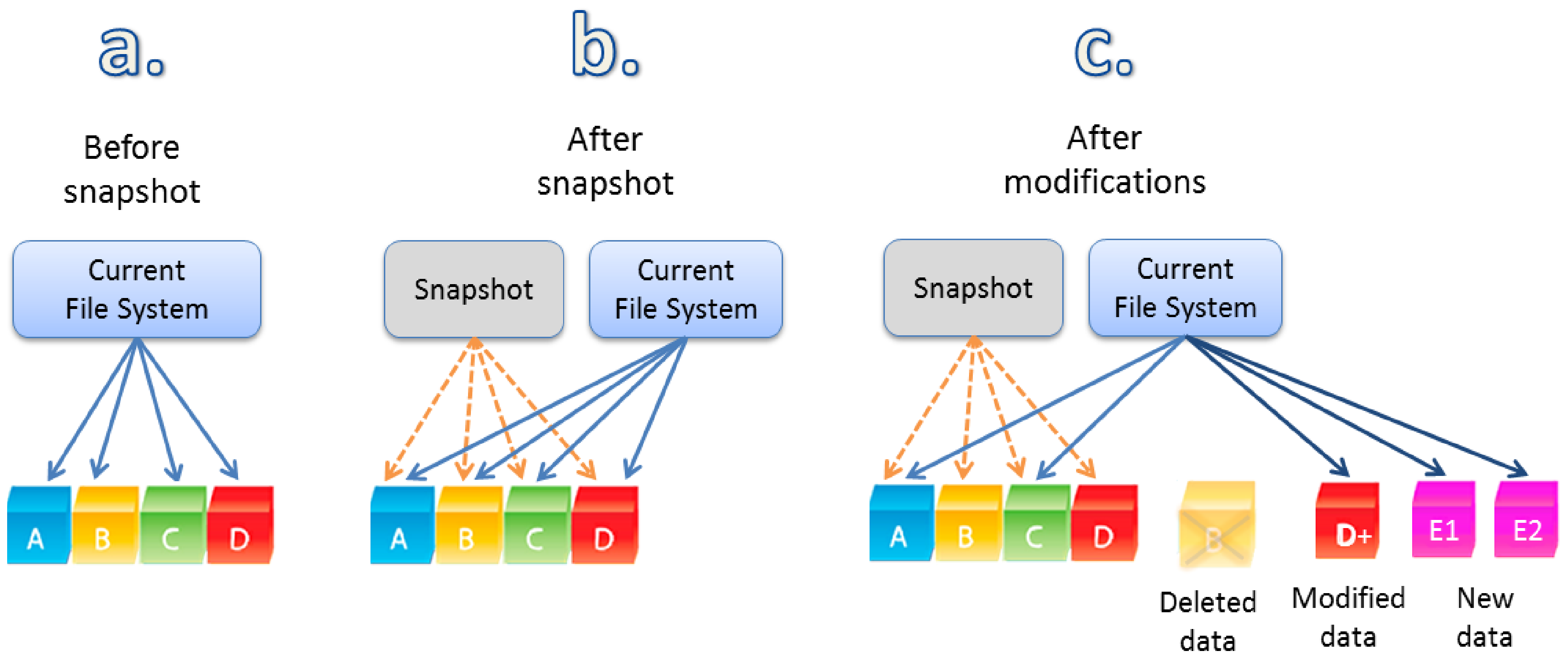
Zoom of WAFL Meta-Data (Tree of Blocks)

- Root inode must be in fixed location
- Other blocks can be written anywhere



Snapshots (1 of 2)

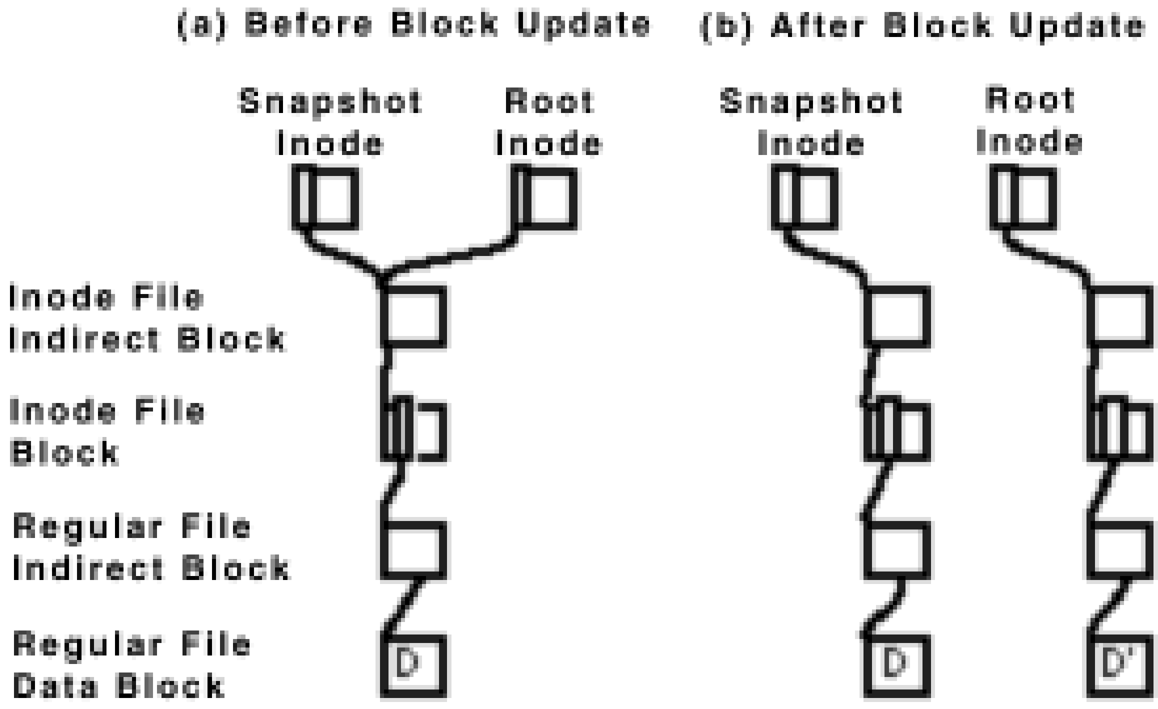
- Copy root inode only, copy on write for changed data blocks



- Over time, old snapshot references more and more data blocks that are not used
- Rate of file change determines how many snapshots can be stored on system

Snapshots (2 of 2)

- When disk block modified, must modify meta-data (indirect pointers) as well



- Batch, to improve I/O performance

Consistency Points (1 of 2)

- In order to avoid consistency checks after unclean shutdown, WAFL creates special snapshot called *consistency point* every few seconds
  - Not accessible via NFS
- Batched operations are written to disk each consistency point
  - Like journal
- In between consistency points, data only written to RAM

Consistency Points (2 of 2)

- WAFL uses NVRAM (NV = Non-Volatile):
  - (NVRAM is DRAM with batteries to avoid losing during unexpected poweroff, some servers now just solid-state or hybrid)
  - NFS requests are logged to NVRAM
  - Upon unclean shutdown, re-apply NFS requests to last consistency point
  - Upon clean shutdown, create consistency point and turnoff NVRAM until needed (to save power/batteries)
- Note, typical FS uses NVRAM for metadata write cache instead of just logs
  - Uses more NVRAM space (WAFL logs are smaller)
    - Ex: "rename" needs 32 KB, WAFL needs 150 bytes
    - Ex: write 8 KB needs 3 blocks (data, inode, indirect pointer), WAFL needs 1 block (data) plus 120 bytes for log
  - Slower response time for typical FS than for WAFL (although WAFL may be a bit slower upon restart)

Write Allocation

- Write times dominate NFS performance
  - Read caches at client are large
  - Up to 5*x* as many write operations as read operations at server
- WAFL batches write requests (e.g., at consistency points)
- WAFL allows “write anywhere”, enabling inode next to data for better perf
  - Typical FS has inode information and free blocks at fixed location
- WAFL allows writes in any order since uses consistency points
  - Typical FS writes in fixed order to allow `fsck` to work if unclean shutdown

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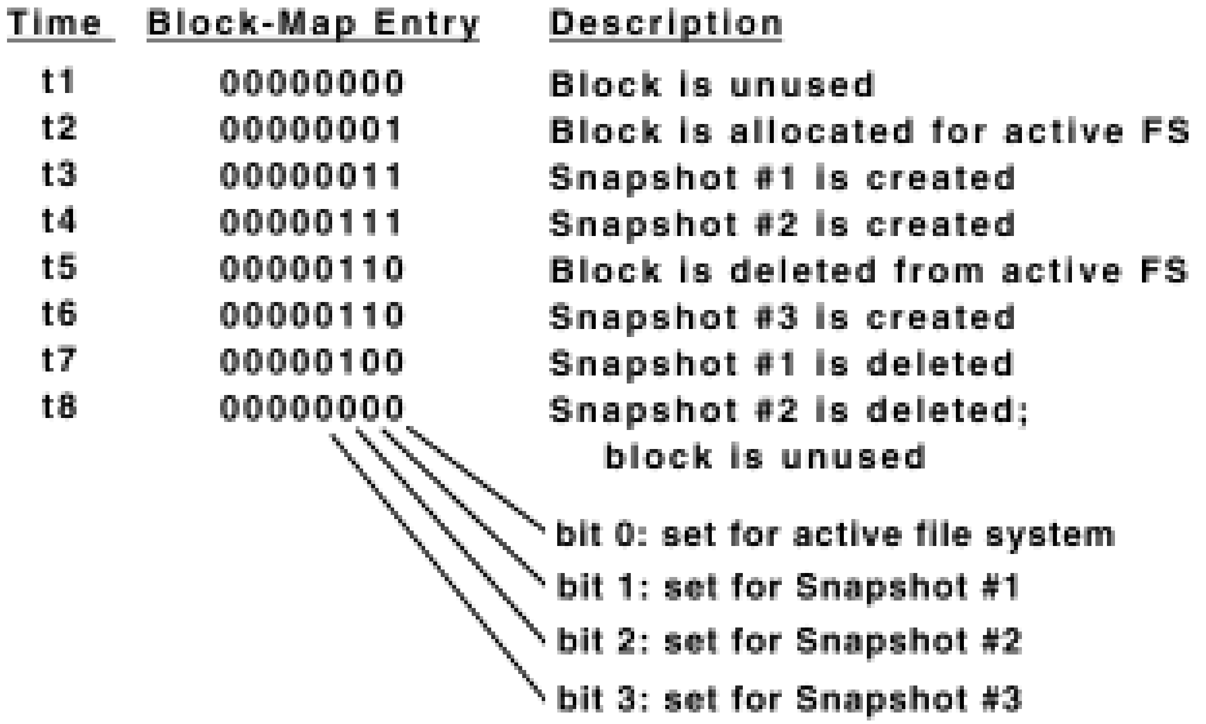
The Block-Map File

- Typical FS uses bit for each free block, 1 is allocated and 0 is free
  - Ineffective for WAFL since may be other snapshots that point to block
- WAFL uses 32 bits for each block
  - For each block, copy "active" bit over to snapshot bit



Time	Block-Map Entry	Description
t1	00000000	Block is unused
t2	00000001	Block is allocated for active FS
t3	00000011	Snapshot #1 is created
t4	00000111	Snapshot #2 is created
t5	00000110	Block is deleted from active FS
t6	00000110	Snapshot #3 is created
t7	00000100	Snapshot #1 is deleted
t8	00000000	Snapshot #2 is deleted; block is unused

bit 0: set for active file system
bit 1: set for Snapshot #1
bit 2: set for Snapshot #2
bit 3: set for Snapshot #3

Outline

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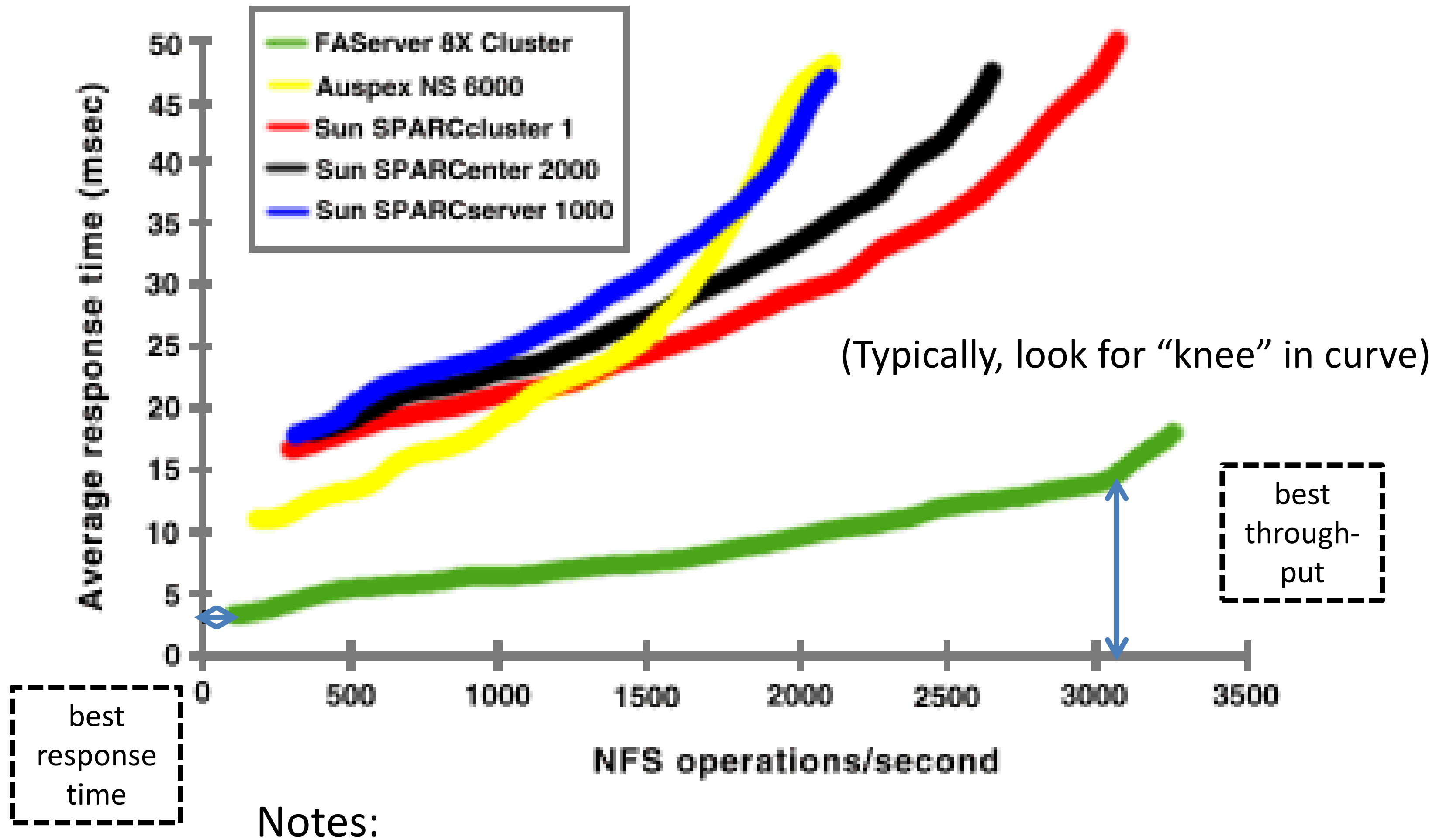
Performance (1 of 2)

- Compare against other NFS systems
- How to measure NFS performance?
  - Best is SPEC NFS
    - LADDIS: Legato, Auspex, Digital, Data General, Interphase and Sun
- Measure response times versus throughput
  - Typically, servers quick at low throughput then response time increases as throughput requests increase

Performance (2 of 2)



Notes:

+ FAS has only 8 file systems, and others have dozens

- FAS tuned to NFS, others are general purpose

Conclusion

- NetApp (with WAFL) works and is stable
  - – Consistency points simple, reducing bugs in code
  - – Easier to develop stable code for network appliance than for general system
    - Few NFS client implementations and limited set of operations so can test thoroughly
- WPI bought one ☺