Lecture 15: Filesystem Implementations

CS343 – Operating Systems
Branden Ghena – Spring 2024

Some slides borrowed from:
Stephen Tarzia (Northwestern), Shivaram Venkataraman (Wisconsin), Ed Lazowska (Washington), and UC Berkeley CS162

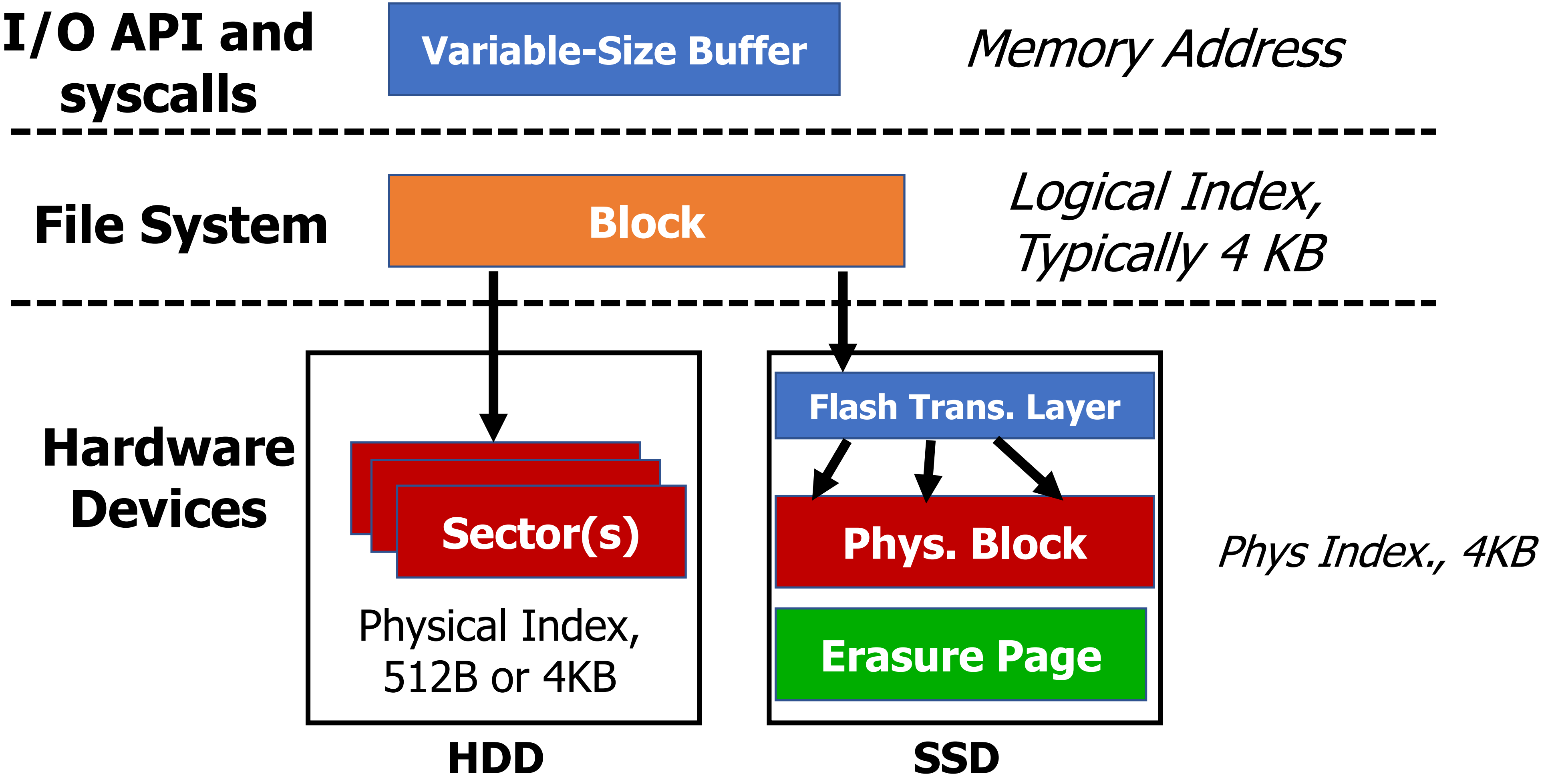
Northwestern

Today’s Goals

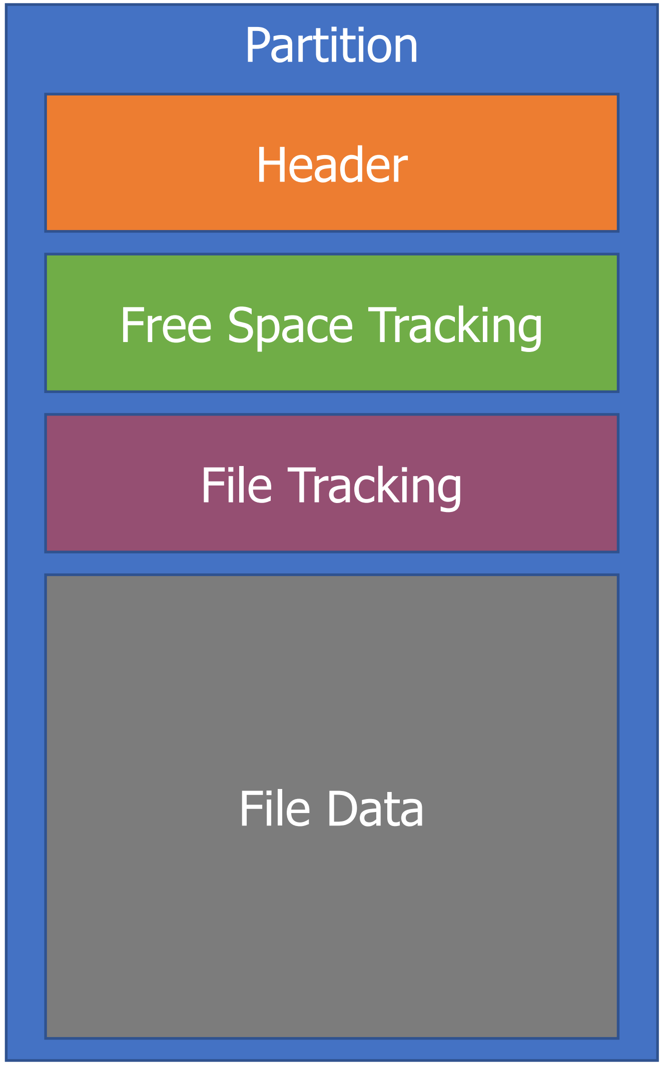
- Understand about additional filesystem features
    - Performance: disk caching
    - Reliability: checking, journaling, and copy-on-write

- Explore real-world filesystem designs
    - FAT, FFS, ext3/ext4, NTFS, ZFS

File systems abstractions



What goes within a partition?



- Header (Superblock)
  - Details about which filesystem this is
  - Metadata about the filesystem
- Free Space Tracking
  - Likely a bitmap of whether blocks are used/free
- File Tracking
  - Either allocation table or inodes
- File Data

Create and write a file

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]	
create (/foo/bar)			**read**								1
						read					
				read							
							read				
		read									2
		write									
							write				3
					write						4
				write							
write()					**read**						
	read										
	write										
								write			
					write						
write()					**read**						
	read										
	write										
									write		
					write						
write()					**read**						
	read										
	write										
										write	
					write						

Create:

1. First, read the parent directory to ensure that name is not already used.
2. Find & claim a free inode.
3. Add <"bar", inode#> to parent directory.
4. Fill-in file metadata.

Create and write a file

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]
create (/foo/bar)			read							
						read		1		
				read						
							read			
		read	2							
		write								
							write	3		
					write	4				
				write						
write()					read	1				
	read	2								
	write									
								write	3	
					write	4				
write()					read					
	read									
	write									
									write	
					write					
write()					read					
	read									
	write									
										write
					write					

Create:

1. First, read the parent directory to ensure that name is not already used.
2. Find & claim a free inode.
3. Add <"bar", inode#> to parent directory.
4. Fill-in file metadata.

Write:

1. Look for remaining space in existing blocks first.
2. Find & claim a new data block.
3. Write data to new block
4. Point to it in inode

Outline

- **Disk Caching**

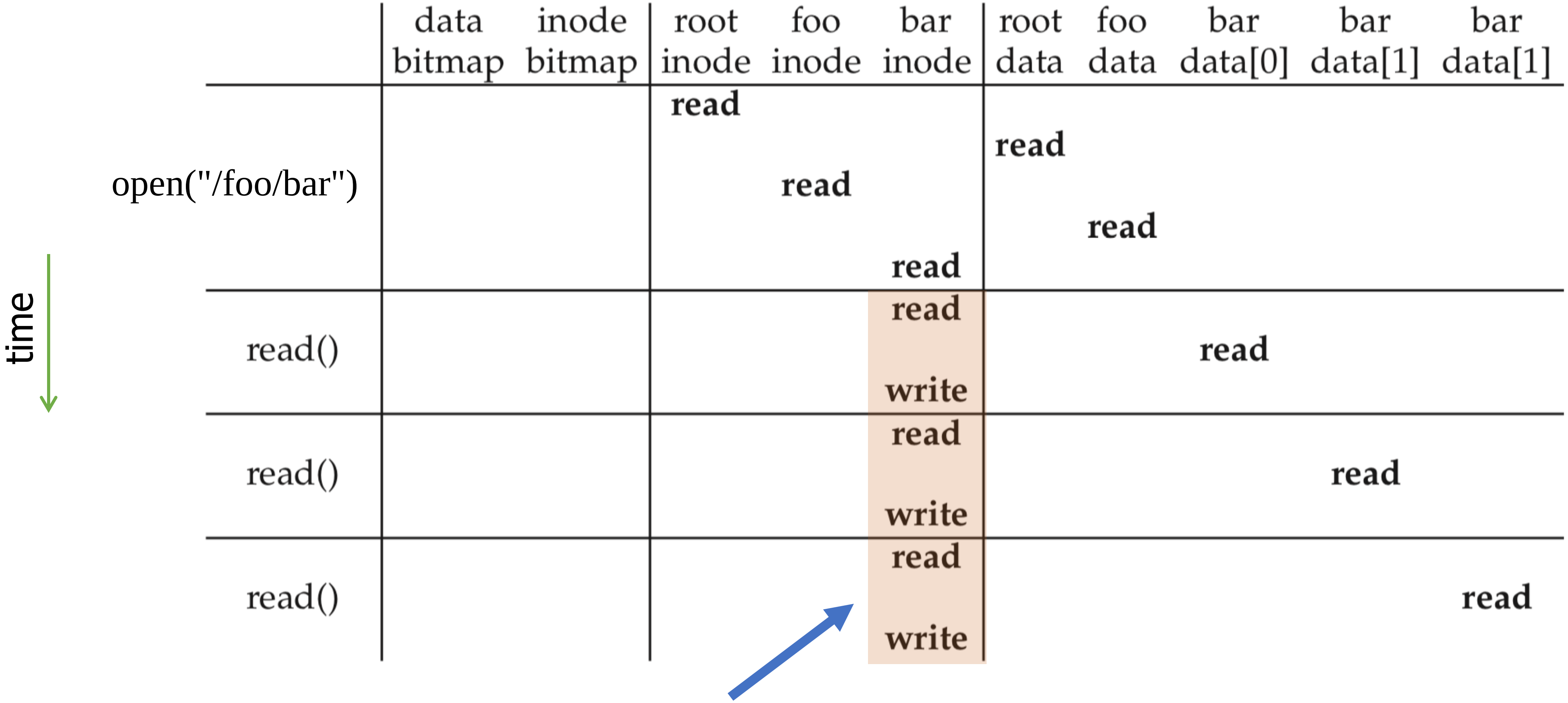
- Classical Filesystems
  - FAT
  - FFS

- Improving Reliability
  - FSCK
  - Journaling

- Journaling Filesystems
  - ext3/ext4
  - NTFS

- Copy-On-Write
  - ZFS

Many disk interactions should be hitting memory instead

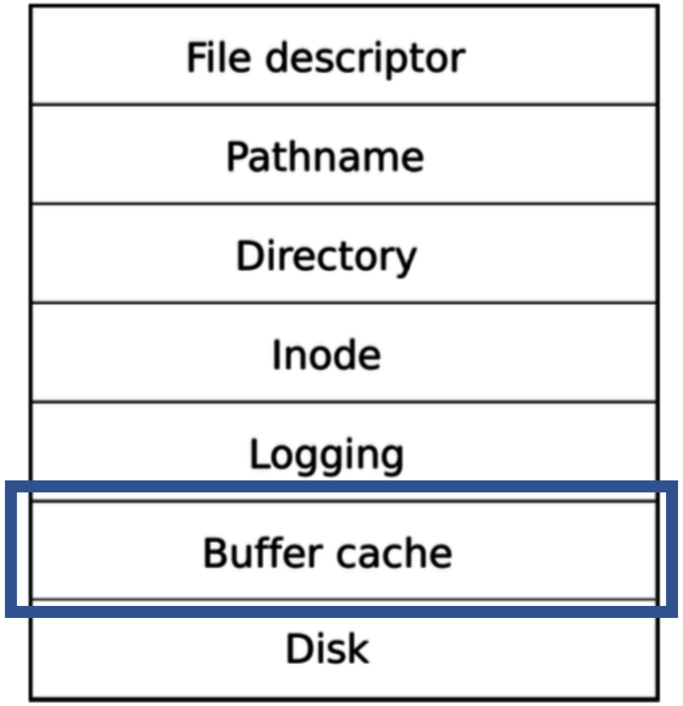


	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]
open("/foo/bar")			read							
						read				
				read						
							read			
					read					
read()					read					
								read		
					write					
read()					read					
									read	
					write					
read()					read					
										read
					write					

inode reads/writes
occur in memory

Filesystem caching

- File I/O can be a significant bottleneck
- So keep useful parts of disk in RAM!
  - Improves performance
- OS kernel does this automatically
  - Using unused RAM to hold disk blocks



File descriptor

Pathname

Directory

Inode

Logging

Buffer cache

Disk

Goals for filesystem caching

1. Cache popular blocks so the disk can be accessed less frequently.
    - Recall that disk has 10,000× greater delay than RAM.
    - ***Reads*** are faster if the disk block is already in memory from a recent access.
    - ***Writes*** can be aggregated.
        - If a thread writes three times briefly to the same file, these can likely be reduced to one write to disk if the writes are delayed.
        - If a thread creates a new file and quickly deletes it, these writes can be skipped altogether.
    - Eventually, changes must be flushed to disk, but there is no rush.

2. Must be careful to prevent two threads from accessing different unsynchronized copies of the disk block.
    - i.e., make the cache **coherent** and avoid race conditions

Unified Page Cache

- Page replacement policy can simultaneously consider both pages from Virtual Memory and pages cached from disk
  - May choose to evict either if needed

- Priority:
  1. Unwritten disk files or unmodified anonymous memory pages
     - Situational which is more important, but neither requires writeback

  2. Written disk files
     - Going to have to be written to disk eventually anyways

  3. Modified memory pages
     - Must go to swap space to be later read again

Prefetching

- Any cache can “prefetch”, loading memory *before* it’s needed

- Base idea: read multiple blocks from disk sequentially from each access
- Advanced: load specific files based on usage patterns
    - The user always opens Powerpoint, so load its data onto disk at boot

- Need to balance prefetching requests with other disk access
    - Don’t want to slow down real accesses with possibly needed prefetching

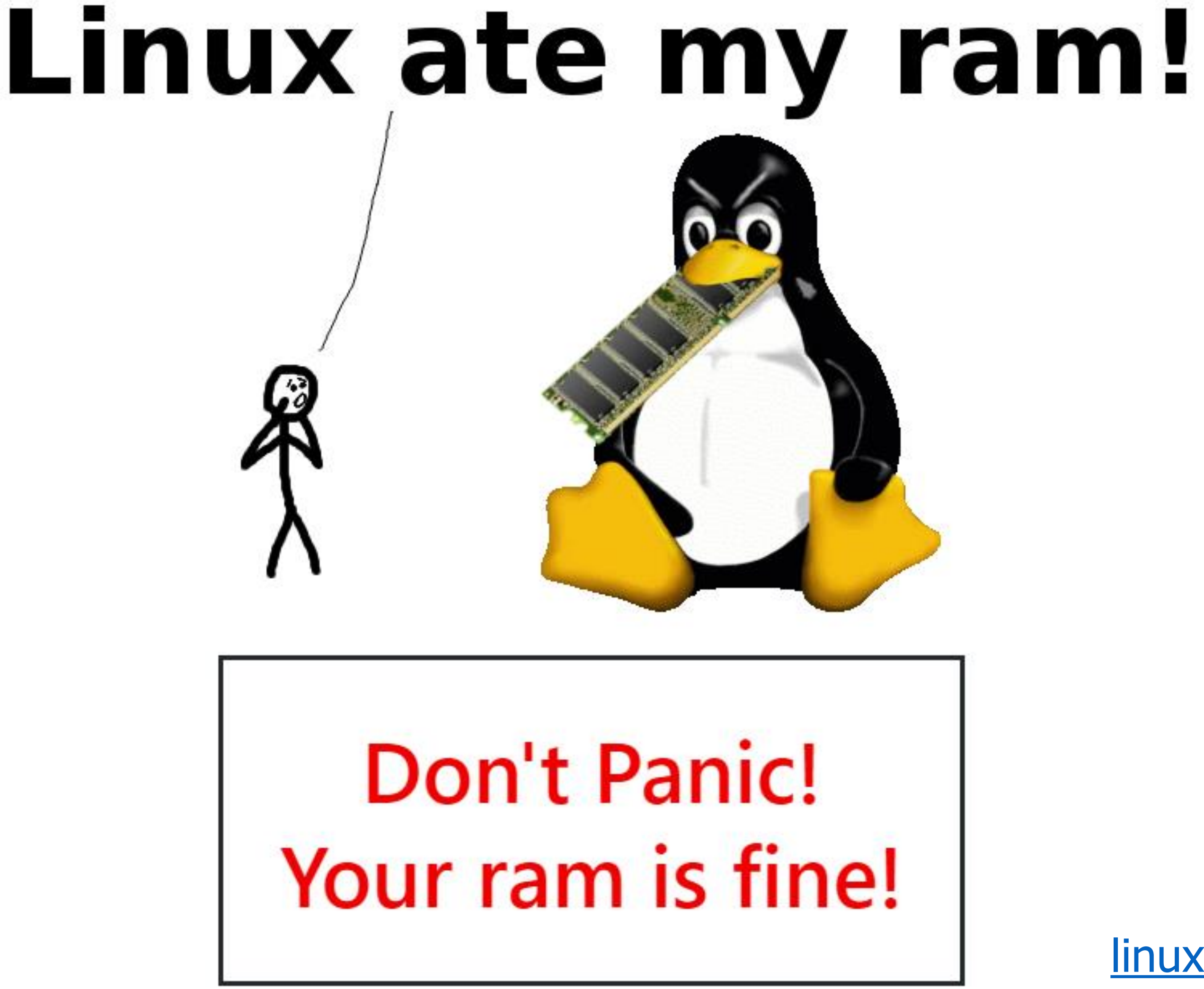
Short break + Question

- What percentage of memory should an OS fill with disk pages?

Short break + Question

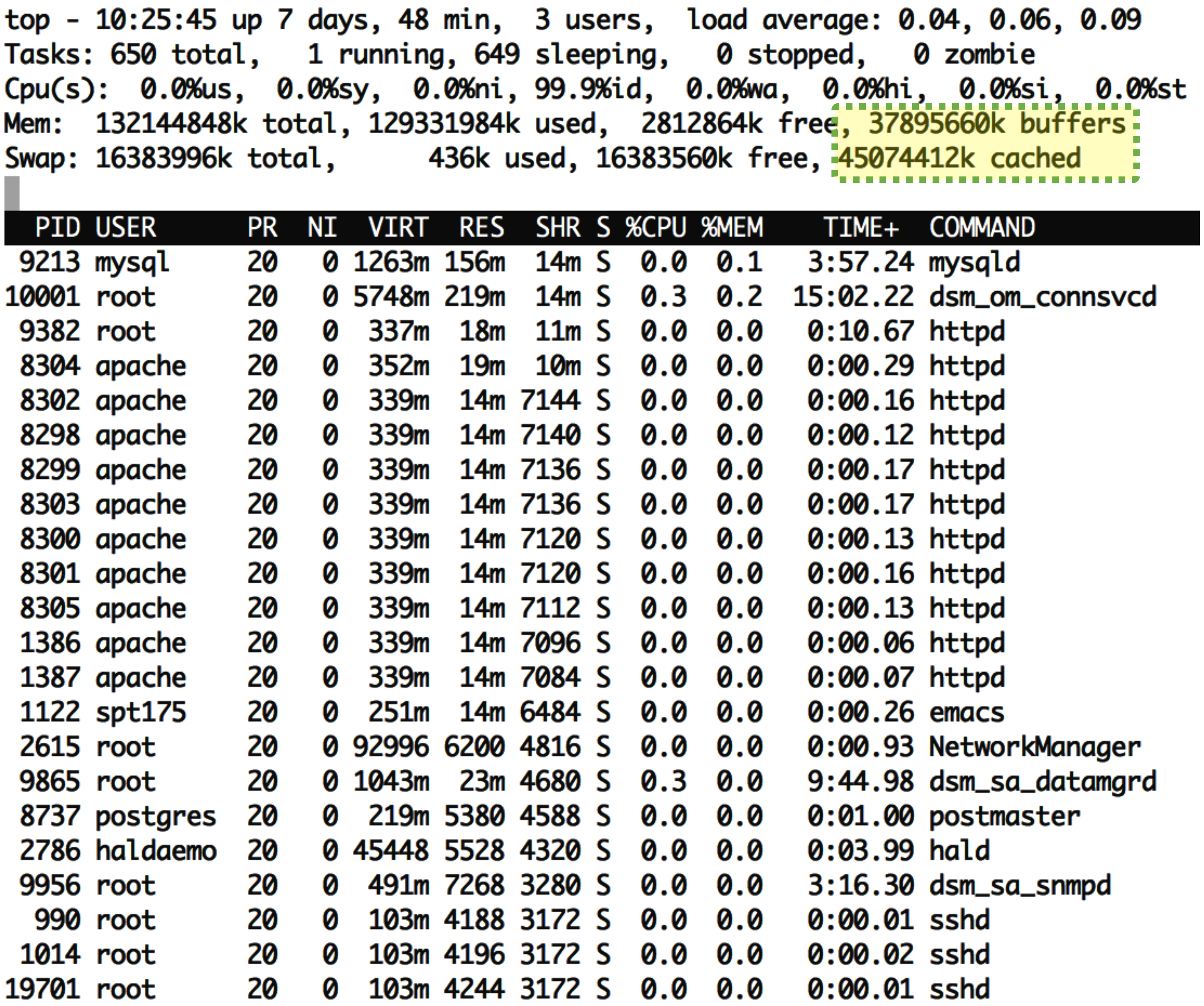
- What percentage of memory should an OS fill with disk pages?
    - As long as it can do it in the background, as much as possible!
    - There’s no particular downside:
        - As long as the page wasn’t written to,
          the RAM can be repurposed later if needed
          without requiring additional writes to disk
    - (Maybe energy use is a downside?)

Real OSes aggressively cache disk in unused RAM



linuxatemyram.com

Real OSes aggressively cache disk in unused RAM



```
top - 10:25:45 up 7 days, 48 min,  3 users,  load average: 0.04, 0.06, 0.09
Tasks: 650 total,   1 running, 649 sleeping,   0 stopped,   0 zombie
Cpu(s):  0.0%us,  0.0%sy,  0.0%ni, 99.9%id,  0.0%wa,  0.0%hi,  0.0%si,  0.0%st
Mem:  132144848k total, 129331984k used,  2812864k free, 37895660k buffers
Swap: 16383996k total,      436k used, 16383560k free, 45074412k cached

  PID USER      PR  NI  VIRT  RES  SHR S %CPU %MEM    TIME+  COMMAND
 9213 mysql     20   0 1263m 156m  14m S  0.0  0.1   3:57.24 mysqld
10001 root      20   0 5748m 219m  14m S  0.3  0.2  15:02.22 dsm_om_connsvcd
 9382 root      20   0  337m  18m  11m S  0.0  0.0   0:10.67 httpd
 8304 apache    20   0  352m  19m  10m S  0.0  0.0   0:00.29 httpd
 8302 apache    20   0  339m  14m 7144 S  0.0  0.0   0:00.16 httpd
 8298 apache    20   0  339m  14m 7140 S  0.0  0.0   0:00.12 httpd
 8299 apache    20   0  339m  14m 7136 S  0.0  0.0   0:00.17 httpd
 8303 apache    20   0  339m  14m 7136 S  0.0  0.0   0:00.17 httpd
 8300 apache    20   0  339m  14m 7120 S  0.0  0.0   0:00.13 httpd
 8301 apache    20   0  339m  14m 7120 S  0.0  0.0   0:00.16 httpd
 8305 apache    20   0  339m  14m 7112 S  0.0  0.0   0:00.13 httpd
 1386 apache    20   0  339m  14m 7096 S  0.0  0.0   0:00.06 httpd
 1387 apache    20   0  339m  14m 7084 S  0.0  0.0   0:00.07 httpd
 1122 spt175    20   0  251m  14m 6484 S  0.0  0.0   0:00.26 emacs
 2615 root      20   0 92996 6200 4816 S  0.0  0.0   0:00.93 NetworkManager
 9865 root      20   0 1043m  23m 4680 S  0.3  0.0   9:44.98 dsm_sa_datamgrd
 8737 postgres  20   0  219m 5380 4588 S  0.0  0.0   0:01.00 postmaster
 2786 haldaemo  20   0 45448 5528 4320 S  0.0  0.0   0:03.99 hald
 9956 root      20   0  491m 7268 3280 S  0.0  0.0   3:16.30 dsm_sa_snmpd
  990 root      20   0  103m 4188 3172 S  0.0  0.0   0:00.01 sshd
 1014 root      20   0  103m 4196 3172 S  0.0  0.0   0:00.02 sshd
19701 root      20   0  103m 4244 3172 S  0.0  0.0   0:00.01 sshd
```

- *buffers* and *cached* both represent file data that is being stored in memory for improved performance
  - Still available for programs
  - Just being made useful for now by caching disk

- Might be a lot of RAM's use for big systems
  - Total RAM: 128 GB
  - Disk cache: 83 GB

Outline

- Disk Caching
- **Classical Filesystems**
  - **FAT**
  - **FFS**
- Improving Reliability
  - FSCK
  - Journaling
- Journaling Filesystems
  - ext3/ext4
  - NTFS
- Copy-On-Write
  - ZFS

FAT (FAT/FAT12/FAT16/FAT32)

- File Allocation Table

- FAT: Microsoft system from *before* MS-DOS (1977)
  - 8 MB max file size
  - 9 character file names
  - No subdirectories

- FAT32: Windows 2000 (introduced 1996)
  - 2 GB max file size
  - 255 character file names
  - Supports up to 16 TB partitions

FAT design choices

- Allocation table for tracking data blocks
  - Requires four bytes per block in the disk
  - File attributes need to be kept in the directory data block

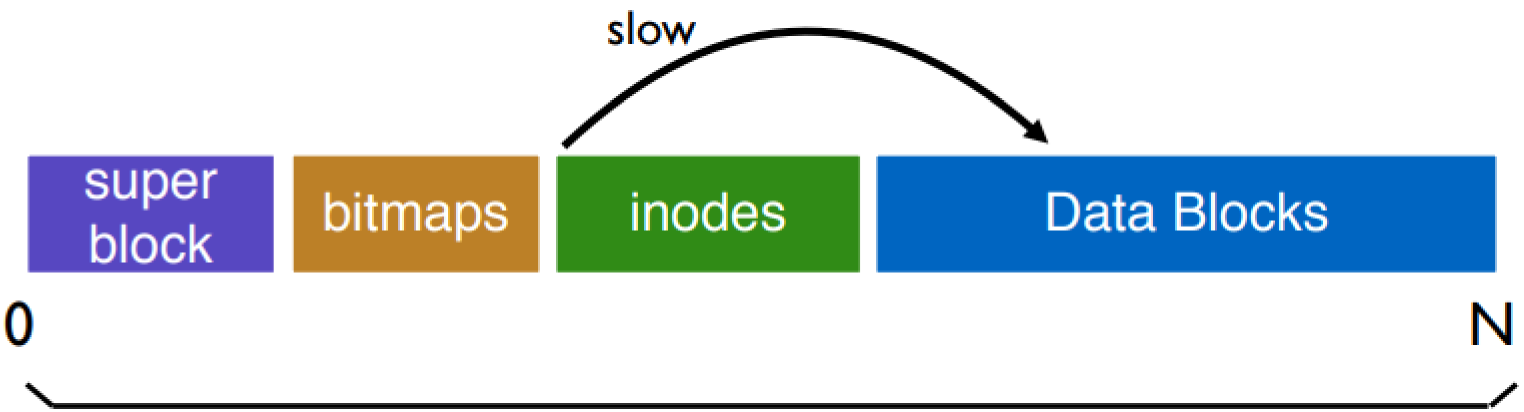
- Still in use for embedded systems
  - Simple to implement
  - Still compatible with modern general-purpose OSes
  - Works fine for relatively small disks with correspondingly small files
    - Think SD cards
  - Implements aggressive block caching

Fast File System (FFS)

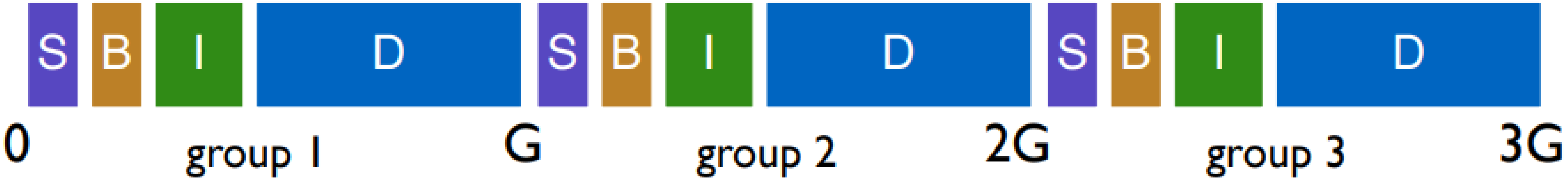
- Unix FileSystem (FS) from 1970
    - inode-based design (combination of all the basic stuff covered last time)
    - Simple and slow
        - inodes are far from data blocks
        - data blocks become fragmented over time

- BSD Fast File System (mid-1980s)
    - First "Disk aware file system"
        - Understands disk seek patterns and sequential access benefits

FFS groups



- Split disk space into a set of "cylinder groups"
  - Each group has its own bitmaps, inodes, and data
  - Keeps data and inodes closer together



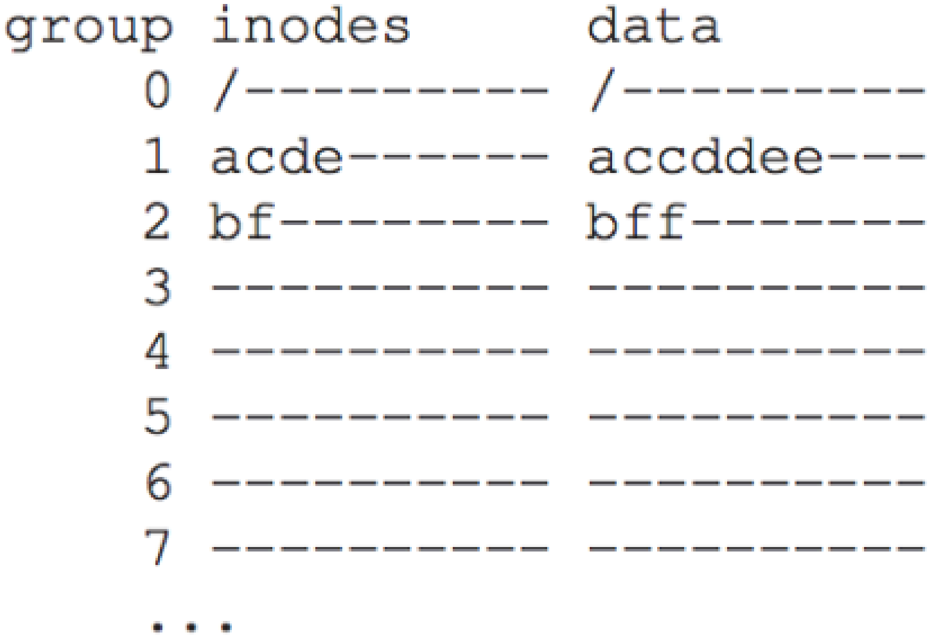
FFS file placement strategy

- General theme: put related pieces of data near each other
- Rules
  1. Put directory data near directory inodes
  2. Put file inodes near directory data
  3. Put data blocks near file inodes

- Example
  - Each directory gets put in an empty group
  - Keep all files within a directory in that single group

FFS example

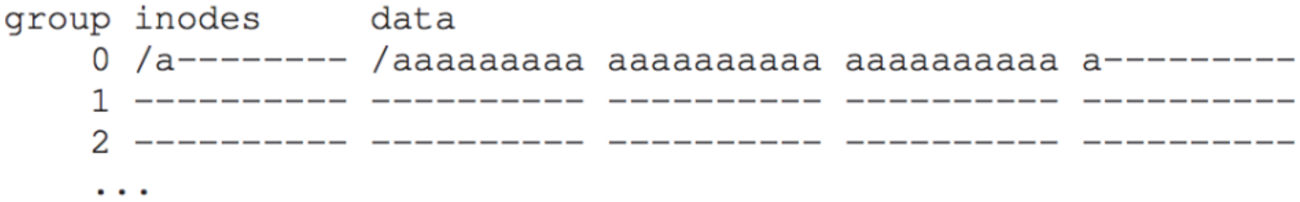
- Example:
  - Directories: **/**, **/a/**, and **/b/**
    - /a/ files: **c**, **d**, **e**
    - /b/ files: **f**



```
group inodes     data
    0 /--------- /---------
    1 acde------ accddee---
    2 bf-------- bff-------
    3 ---------- ----------
    4 ---------- ----------
    5 ---------- ----------
    6 ---------- ----------
    7 ---------- ----------
    ...
```

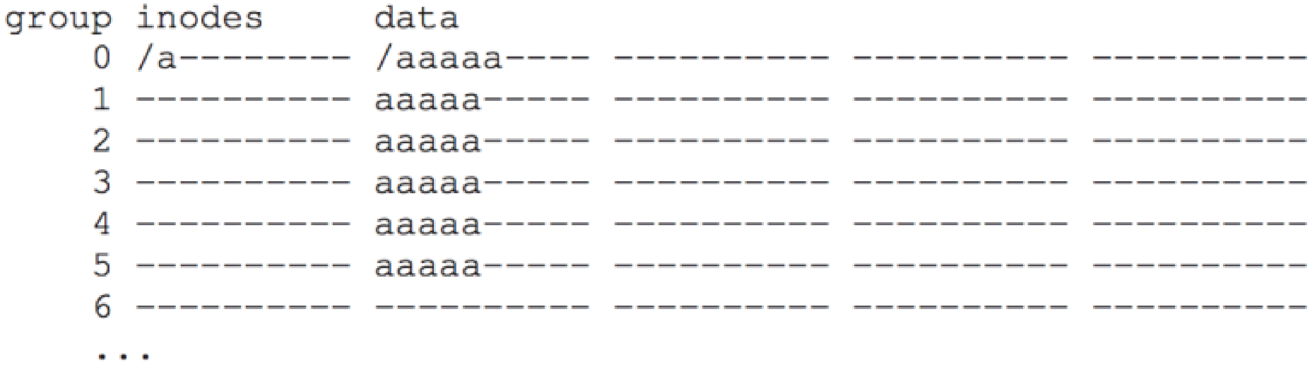
FFS large file problem

- A single large file can fill nearly all of a group
  - So remaining files would have to be placed in other groups



```
group inodes     data
    0 /a-------- /aaaaaaaaa aaaaaaaaaa aaaaaaaaaa a---------
    1 ---------- ---------- ---------- ---------- ----------
    2 ---------- ---------- ---------- ---------- ----------
    ...
```

- Instead, limit filesize per group and place remaining blocks in other groups



```
group inodes     data
    0 /a-------- /aaaaa---- ---------- ---------- ----------
    1 ---------- aaaaa----- ---------- ---------- ----------
    2 ---------- aaaaa----- ---------- ---------- ----------
    3 ---------- aaaaa----- ---------- ---------- ----------
    4 ---------- aaaaa----- ---------- ---------- ----------
    5 ---------- aaaaa----- ---------- ---------- ----------
    6 ---------- ---------- ---------- ---------- ----------
    ...
```

- Most files are small so prioritize them
- Rare, large files will have worse performance

Outline

- Disk Caching

- Classical Filesystems
    - FAT
    - FFS

- **Improving Reliability**
    - **FSCK**
    - **Journaling**

- Journaling Filesystems
    - ext3/ext4
    - NTFS

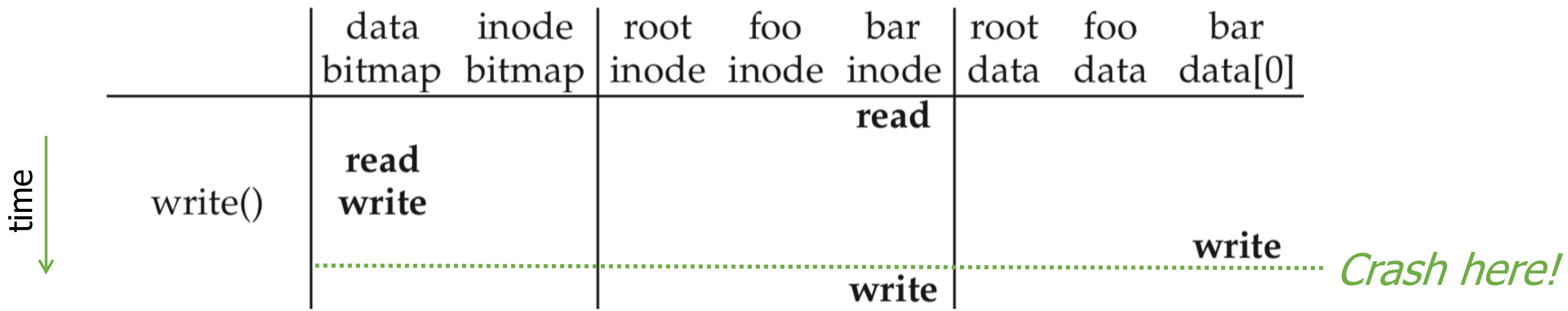
- Copy-On-Write
    - ZFS

Crash tolerance

- Filesystems are persistent and store important data
- They *cannot* rely on a graceful shutdown
  - Power outages happen
  - Kernel might panic
  - USB plug might be yanked out

- File system data structure updates are *critical sections*
  - Not concerned about race conditions, but rather partial updates
  - Transactions should be performed atomically, “all or none”
- All reads and writes aren’t necessarily guaranteed
  - But system needs to stay **consistent**

Crash example (writing to /foo/bar)



	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]
					read			
	read							
write()	**write**							
								write
					write			

Crash here!

- Crash before write to file's inode could leak a data block
    - Data bitmap was updated to reserve data block and data was written
    - But the data block is not pointed to by any inode
    - Block ends up wasted

- Other write orders would be even worse
    - Inode points to a block that hasn't been written and has garbage data
    - Or block is still marked as free in the bitmap, and another file will overwrite it!!

File system checker (FSCK)

- After a crash, scan entire disk for contradictions and “fix”
  - System pauses boot until FSCK completes

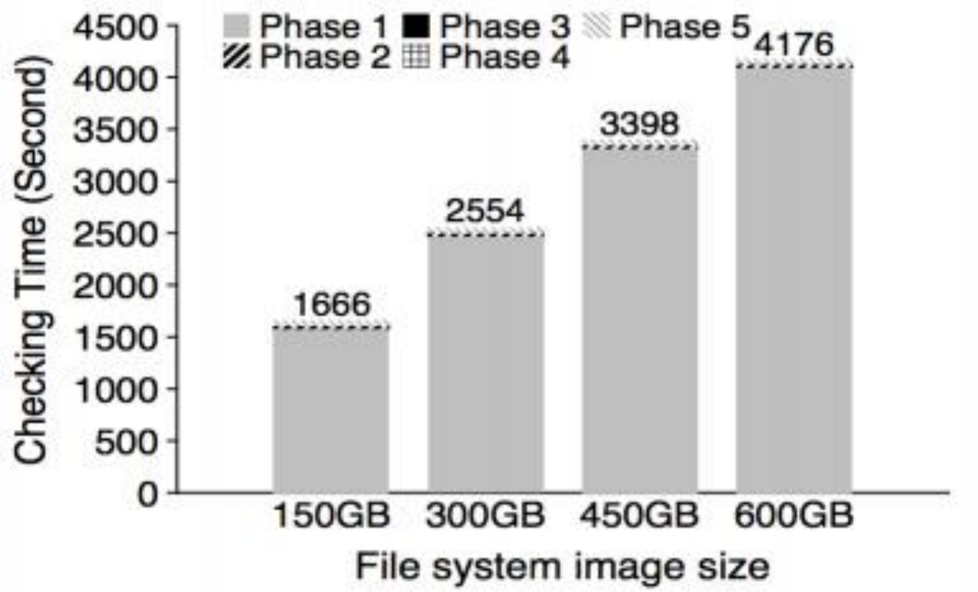
- Example: check data bitmap consistency
  - Read every valid inode
  - Any referenced data block should be marked as used
  - Any used blocks that are not referenced can be marked free

- Also check
  - Each inode should only be listed under one directory (without hard links)
  - Two inodes should not share a data block
  - All block addresses should be valid

Problems with FSCK

1. FSCK makes disks *consistent*, not *correct*
   - Not always obvious how best to fix file system image
   - Trivial way to get consistency: reformat disk

2. FSCK is very slow
   - Reading from disk is slow
   - Reading ALL of disk takes a long time, especially as disks increase in size



Checking a 600GB disk takes ~70 minutes

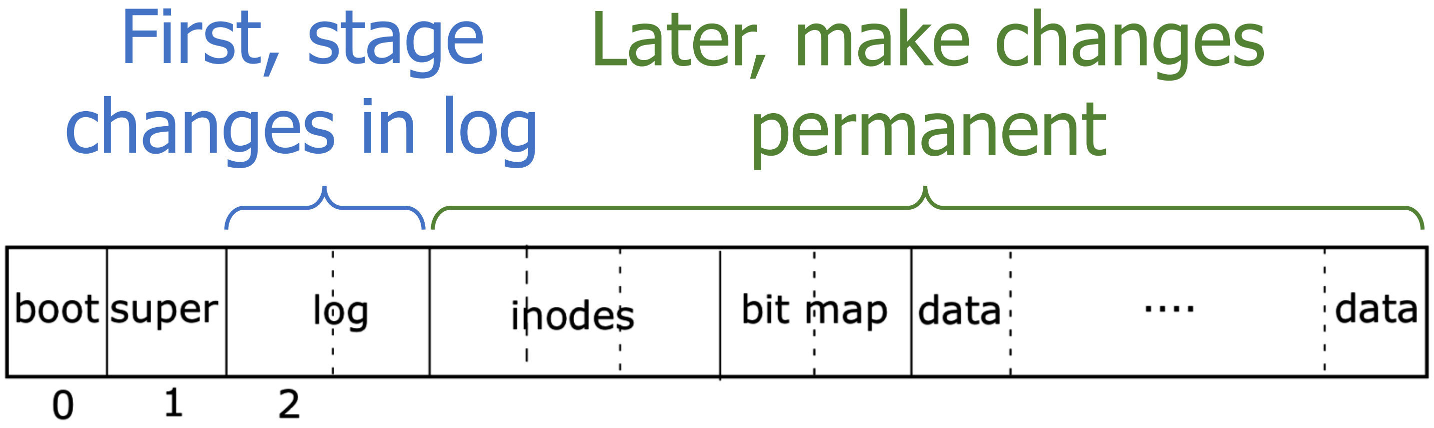
Filesystem transactions

- Goals
  - Move reliability mechanism to continuous operations during runtime
    - Some recovery after crash is fine, but not entire disk
  - Don’t just make file system consistent
    - Guarantee correctness

- Solution: enforce atomic transactions
  - Each transaction must be performed in its entirety or not at all
    - Either all new data is visible
    - Or all old data is visible

Journaling Filesystems

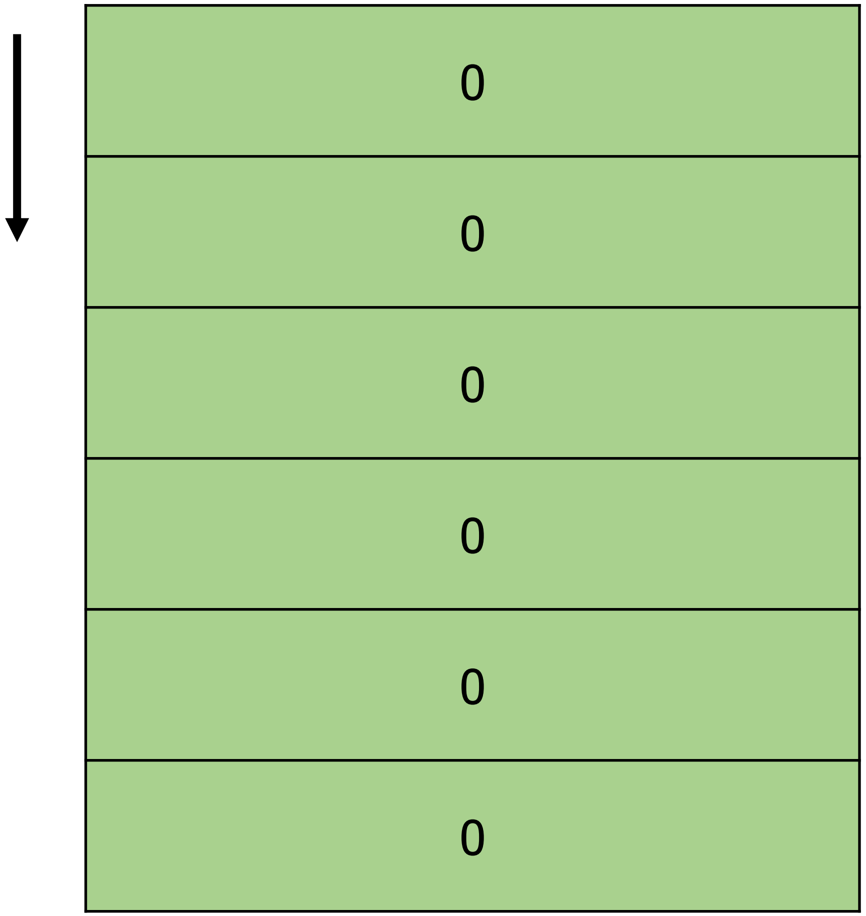
- Write all transactions to *journal* instead of actual locations



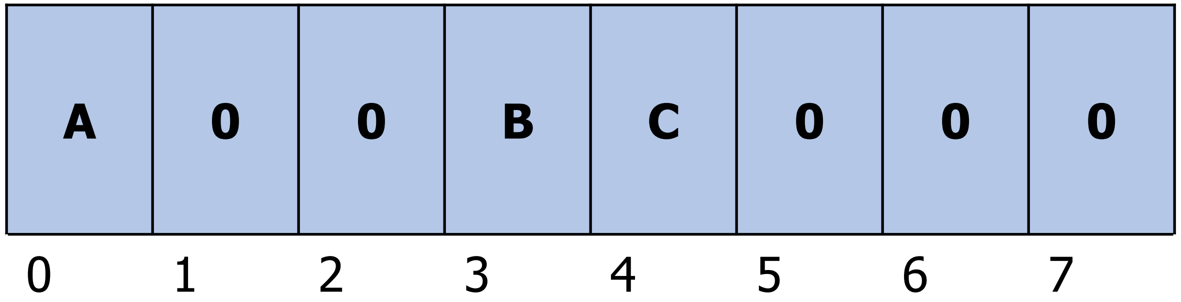
1. Write the blocks to the log, a reserved part of the disk.
   - This makes a durable record of the transaction you plan to commit.
   - Continue putting all writes to the log, until ***commit*** is called.
2. On commit, write a commit message to the log, then start writing all of the logged writes where they belong on disk.
   - Clear the log after everything is written again.

Journaling example

Journal



0
0
0
0
0
0

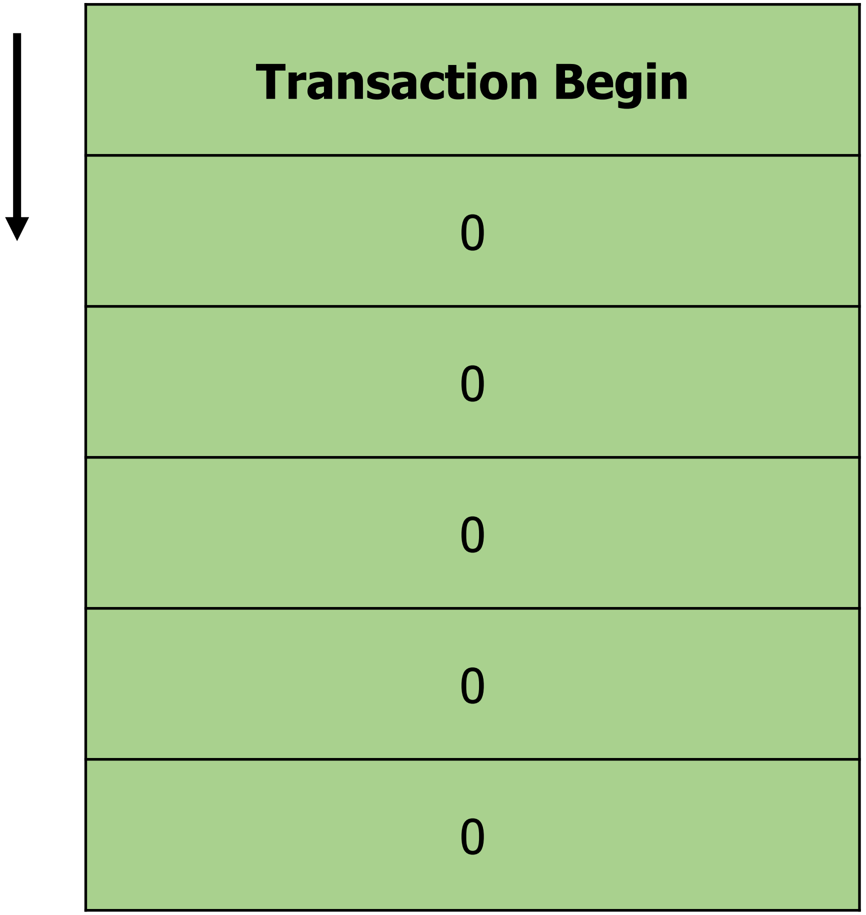


0	1	2	3	4	5	6	7
A	**0**	**0**	**B**	**C**	**0**	**0**	**0**

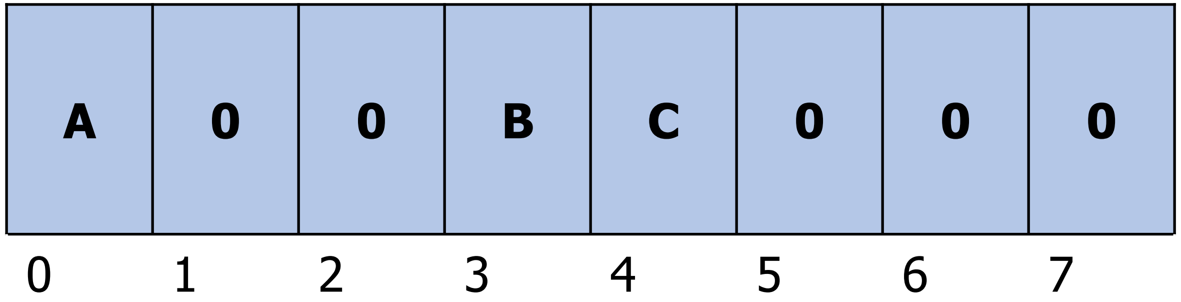
- Current contents of 8 blocks of disk and the journal
  - Note that the journal is also on disk
- Keeping this abstract
  - Blocks could be bitmaps, inodes, data, or anything

Journaling example

Journal



Transaction Begin
0
0
0
0
0



A	**0**	**0**	**B**	**C**	**0**	**0**	**0**
0	1	2	3	4	5	6	7

- Write transaction start to journal

Journaling example

Journal

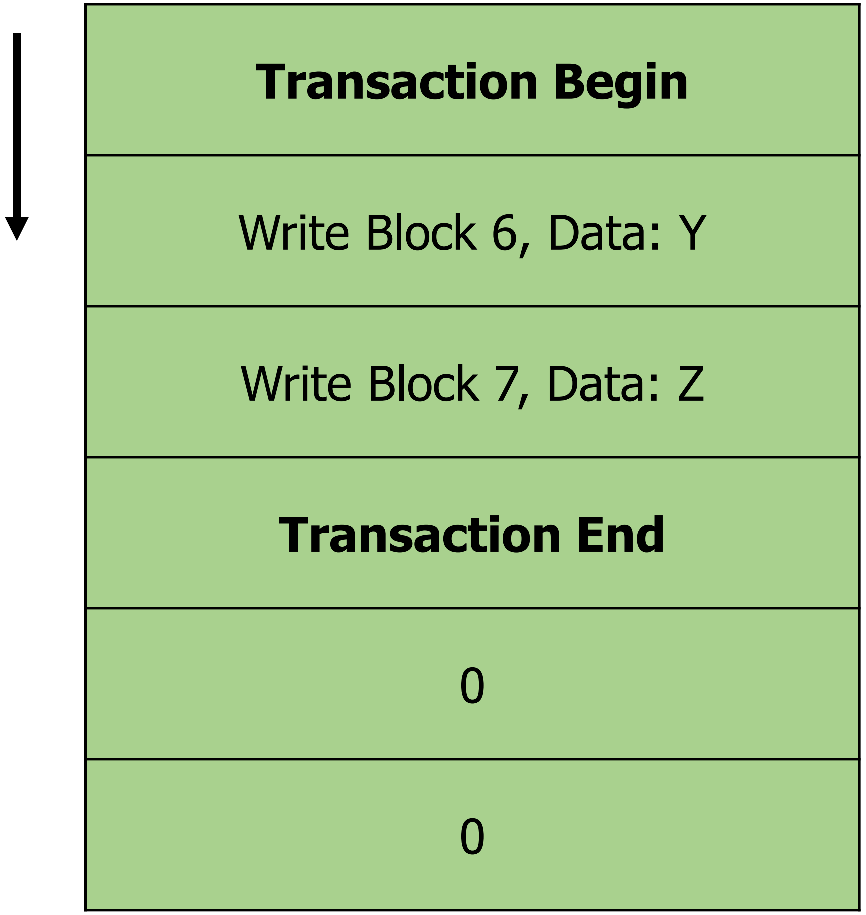
Transaction Begin
Write Block 6, Data: Y
Write Block 7, Data: Z
0
0
0

A	**0**	**0**	**B**	**C**	**0**	**0**	**0**
0	1	2	3	4	5	6	7

- Write transaction start to journal
- Then actions for that transaction
  - Along with the data
  - Journal must be multiple blocks in size

Journaling example

Journal



Transaction Begin

Write Block 6, Data: Y

Write Block 7, Data: Z

Transaction End

0

0

A	**0**	**0**	**B**	**C**	**0**	**0**	**0**
0	1	2	3	4	5	6	7

- Write transaction start to journal
- Then actions for that transaction
  - Along with the data
  - Journal must be multiple blocks in size
- “Commit” by writing transaction end

Journaling example

Journal

Transaction Begin
Write Block 6, Data: Y
Write Block 7, Data: Z
Transaction End
0
0

0	1	2	3	4	5	6	7
A	**0**	**0**	**B**	**C**	**0**	**Y**	**Z**

- Sometime after transaction is written, data can actually be recorded to disk

Journaling example

Journal

0
0
0
0
0
0

A	**0**	**0**	**B**	**C**	**0**	**Y**	**Z**
0	1	2	3	4	5	6	7

- Sometime after transaction is written, data can actually be recorded to disk
- And then journal can be cleared

Resolving crashes with journaling

- The next time the computer boots, OS resolves filesystem:

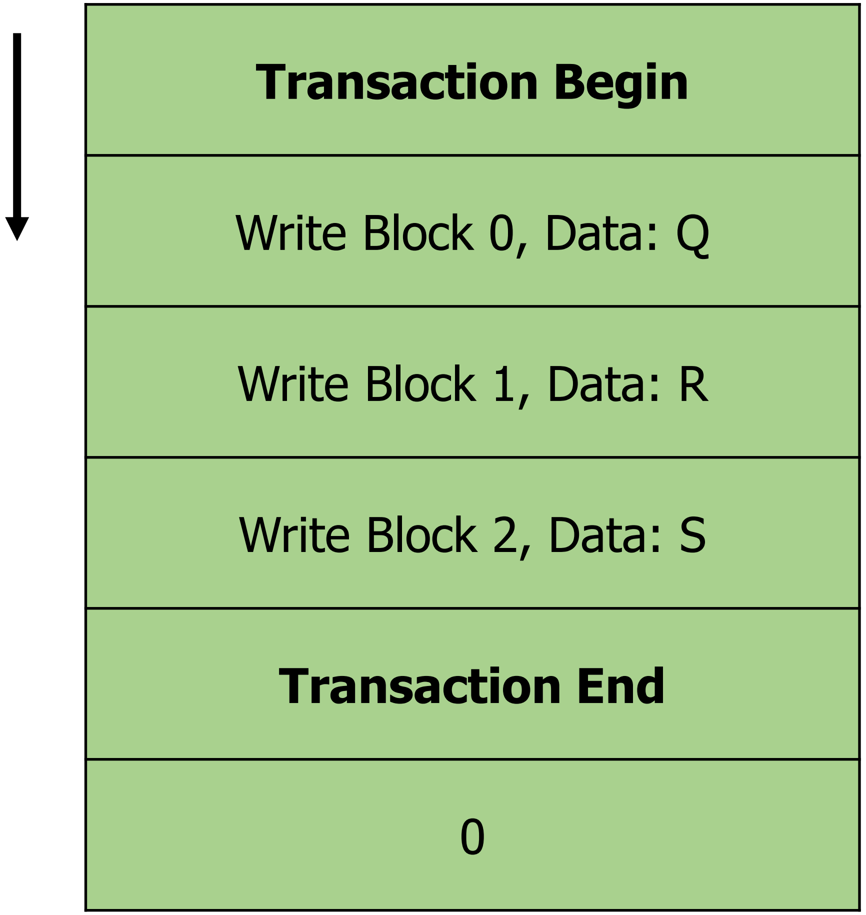
1. No transactions happening when crash occurred
    - Journal is empty. Do nothing because there were no outstanding transactions.

2. Crash occurred *before commit* (before Transaction End):
    - There is data in the journal, but no commit message.
    - Just clear the log to ***roll back*** the transaction.

3. Crash occurred *after commit*, while writing data to main part of disk.
    - We don’t know how much of the transaction was finished.
    - However, the journal tells us exactly what must be done!
    - ***Replay*** the transaction (from the beginning), then clear the journal.

Break + Check your understanding – resolve after crash

Journal



Transaction Begin

Write Block 0, Data: Q

Write Block 1, Data: R

Write Block 2, Data: S

Transaction End

0

Q	**R**	**0**	**B**	**C**	**0**	**Y**	**Z**
0	1	2	3	4	5	6	7

- When did this crash occur?
- What steps should be taken?

Break + Check your understanding – resolve after crash

Journal

Transaction Begin

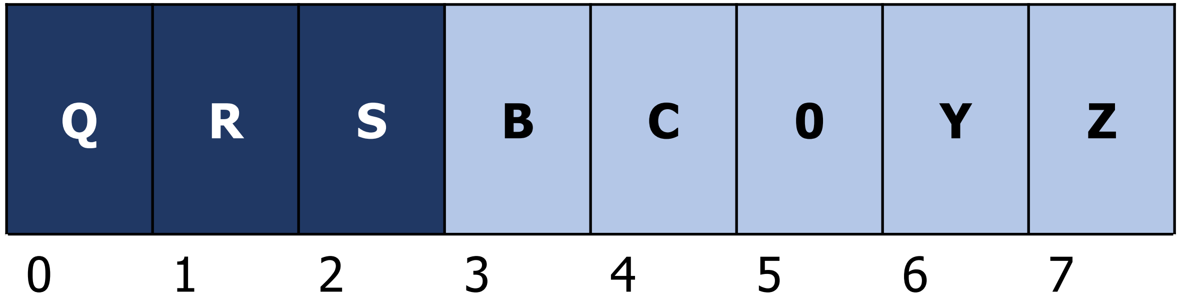
Write Block 0, Data: Q

Write Block 1, Data: R

Write Block 2, Data: S

Transaction End

0



Q	R	S	B	C	0	Y	Z
0	1	2	3	4	5	6	7

- When did this crash occur?
  - After commit
  - Some data may have even been written (impossible to know)
    Note: only look at the journal
- What steps should be taken?
  - Replay transaction and perform the writes

Break + Check your understanding – resolve after crash again

Journal

Transaction Begin
Write Block 3, Data: B
Write Block 4, Data: C
0
0
0

Q	**R**	**0**	**B**	**F**	**0**	**Y**	**Z**
0	1	2	3	4	5	6	7

- When did this crash occur?

- What steps should be taken?

Break + Check your understanding – resolve after crash again

Journal

0
0
0
0
0
0

Q	**R**	**0**	**B**	**F**	**0**	**Y**	**Z**
0	1	2	3	4	5	6	7

- When did this crash occur?
  - Before transaction committed
- What steps should be taken?
  - Delete partial transaction from journal
  - No need to edit disk blocks

Journaling performance

- Transactions only need to be written to the journal for writes

- Interactions with disk can still be cached as before
  - Would be lost in a crash, but no consistency problems
  - Several writes can be combined into one transaction

- Can avoid writing all disk blocks twice by only tracking metadata
  - Writes to bitmaps, inodes, and directories are journaled
  - Writes to file data blocks just happen whenever
    - File could still be corrupted! But the *filesystem* is safe
    - Likely only corrupted in units of whole blocks

Outline

- Disk Caching
- Classical Filesystems
  - FFS
  - FAT
- Improving Reliability
  - FSCK
  - Journaling
- **Journaling Filesystems**
  - **ext3/ext4**
  - **NTFS**
- Copy-On-Write
  - ZFS

ext2/ext3/ext4

- extended filesystem – default for Linux

- ext2 (1993)
  - “Block groups” rather than cylinder groups, of arbitrary size

- ext3 (2001)
  - Adds journaling
  - Configuration options choose to journal either everything or metadata-only

- ext4 (2006)
  - Extents, encryption
  - Used on modern-day linux systems

Extents reduce number of pointers to data blocks

- Extents
  - Instead of raw block addresses
  - Store starting block address and length
  - Greatly compacts sequentially stored data pointers in inodes

- ext4 uses extents
  - 4 extents per file
  - Large, fragmented files use hierarchical system like original inodes

Other ext4 advances

- Encryption
  - Encrypts a directory and all of its contents
  - File names *and* file data
  - AES encrypt/decrypt is performed on data blocks during read/write

- Directory data structure
  - Htree (specialized B-tree)
  - Enables large subdirectory chains and many files with good seek time

NTFS

- NT File System – modern Windows filesystem (1993)
  - Designed for Windows NT (Windows 2000 and up)
  - Uses Master File Table rather than Allocation Table

- Has grown to include many features we’ve seen
  - Journaling
  - Extents
  - Encryption
  - Directories using B-Trees

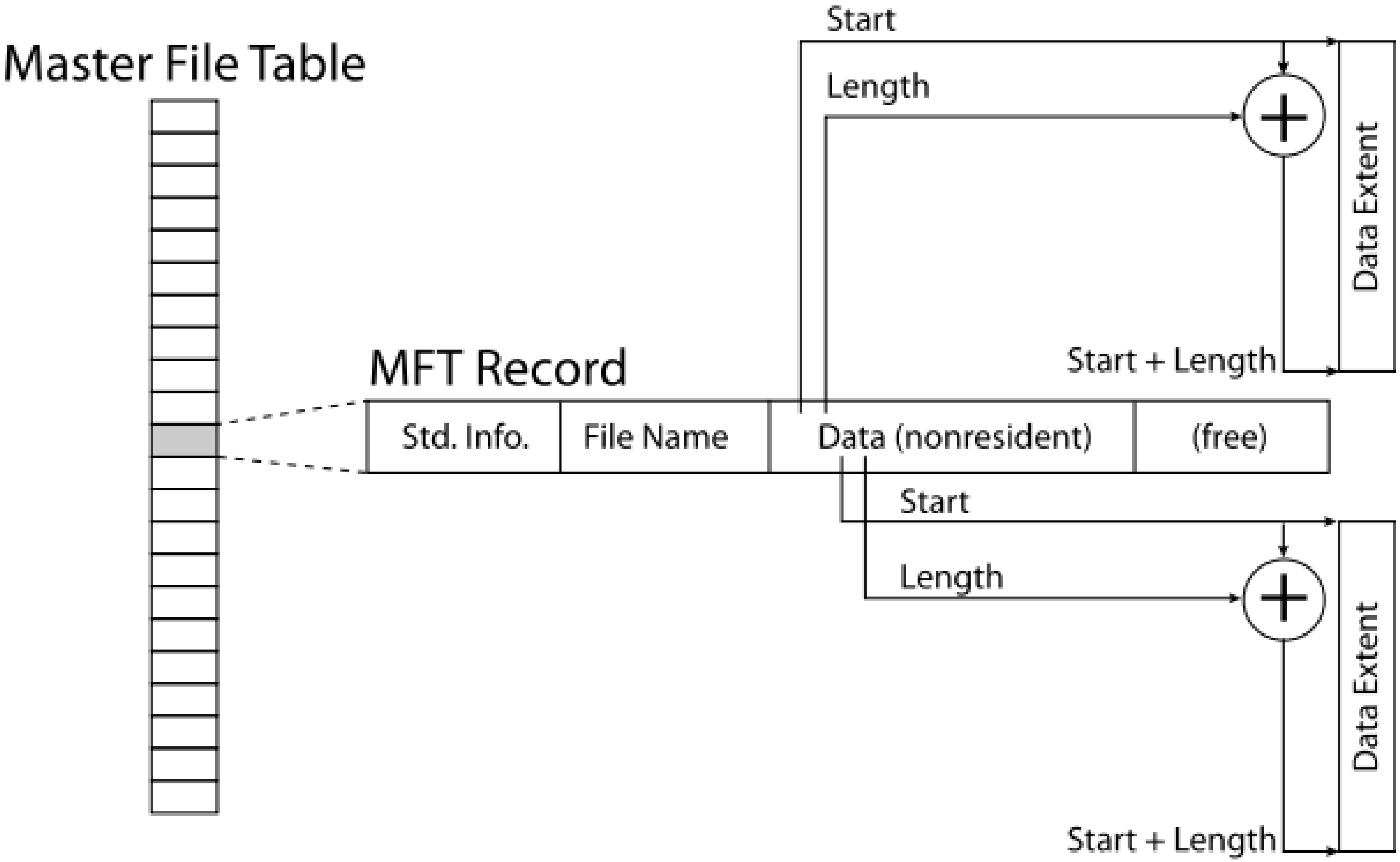
- Adds compression

NTFS Master File Table

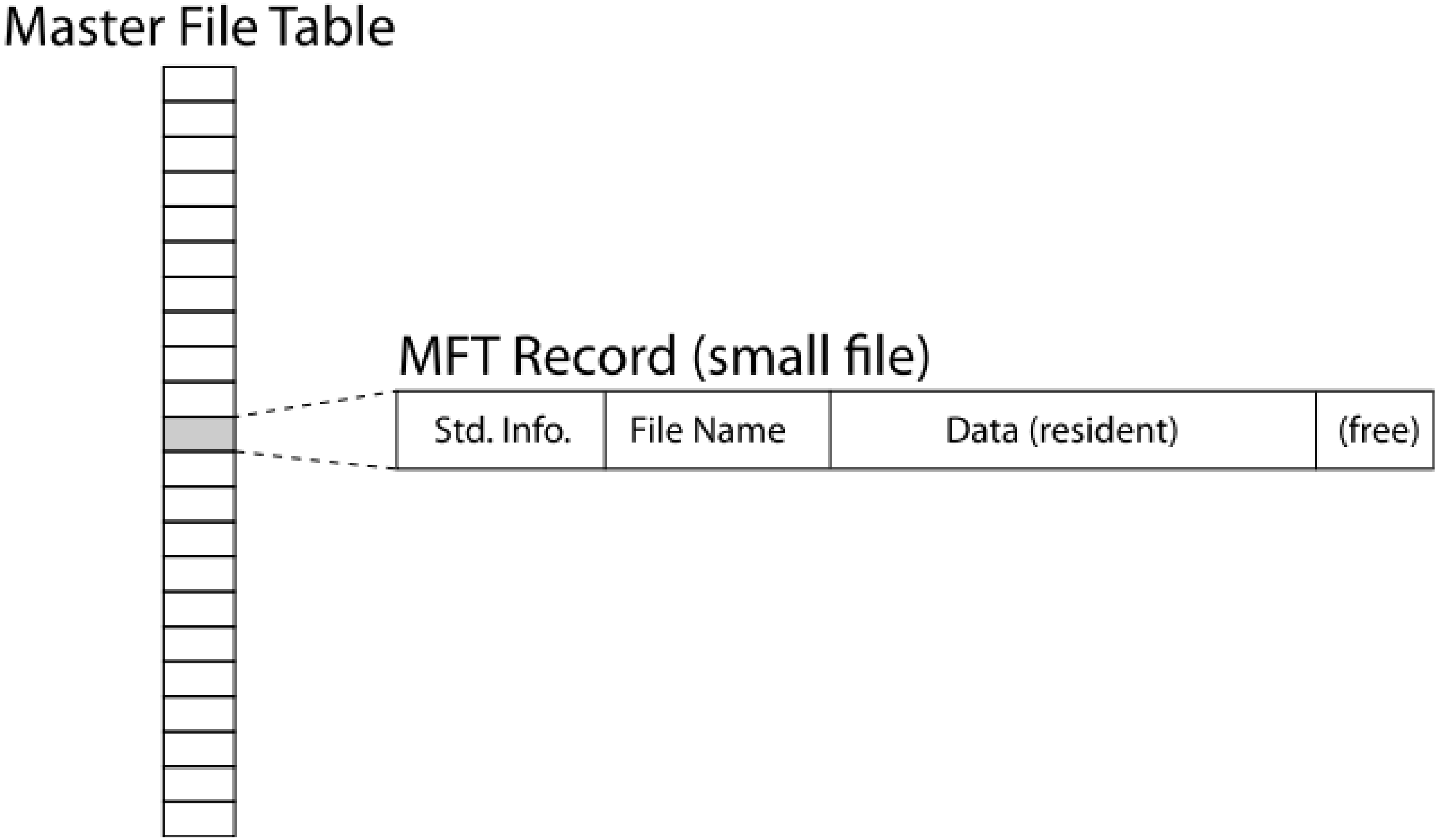
- Master File Table
  - Similar in practice to an array of inodes
  - Usually one MFT record per file
    - But large files can include pointers to additional MFT records

- Each MFT Record contains
  - Standard attributes
  - Name and pointer to parent directory
  - Storage space
    - Can hold extents to point to series of data blocks
    - Can hold pointers to additional MFT records (for more data blocks)
    - Can hold file data itself!! (if small enough)

NTFS with medium-sized, mostly non-fragmented file



NTFS with a small file



NTFS can automatically compress files

- Before write to disk, compress file data blocks
  - Only write smaller compressed data
- After read from disk, decompress file data blocks

- Interesting tradeoff
  - Read less total blocks from disk
  - Spend more CPU time manipulating blocks

Break + Extend Thinking

- In Windows 10, a service compresses infrequently used files
  - What files will this work on and what won't this help with?

Break + Extend Thinking

- In Windows 10, a service compresses infrequently used files
  - What files will this work on and what won’t this help with?

  - Text files are super compressible!!
  - Code binaries are maybe compressible

  - Unfortunately, can’t compress *already compressed* files
    - Particularly: videos and music

Outline

- Disk Caching
- Classical Filesystems
    - FFS
    - FAT
- Improving Reliability
    - FSCK
    - Journaling
- Journaling Filesystems
    - ext3/ext4
    - NTFS
- **Copy-On-Write**
    - **ZFS**

Adding file versioning through copy-on-write

- Correctness could also come with a bonus: ability to version files
    - File could be rolled back to an older version from a prior point in time

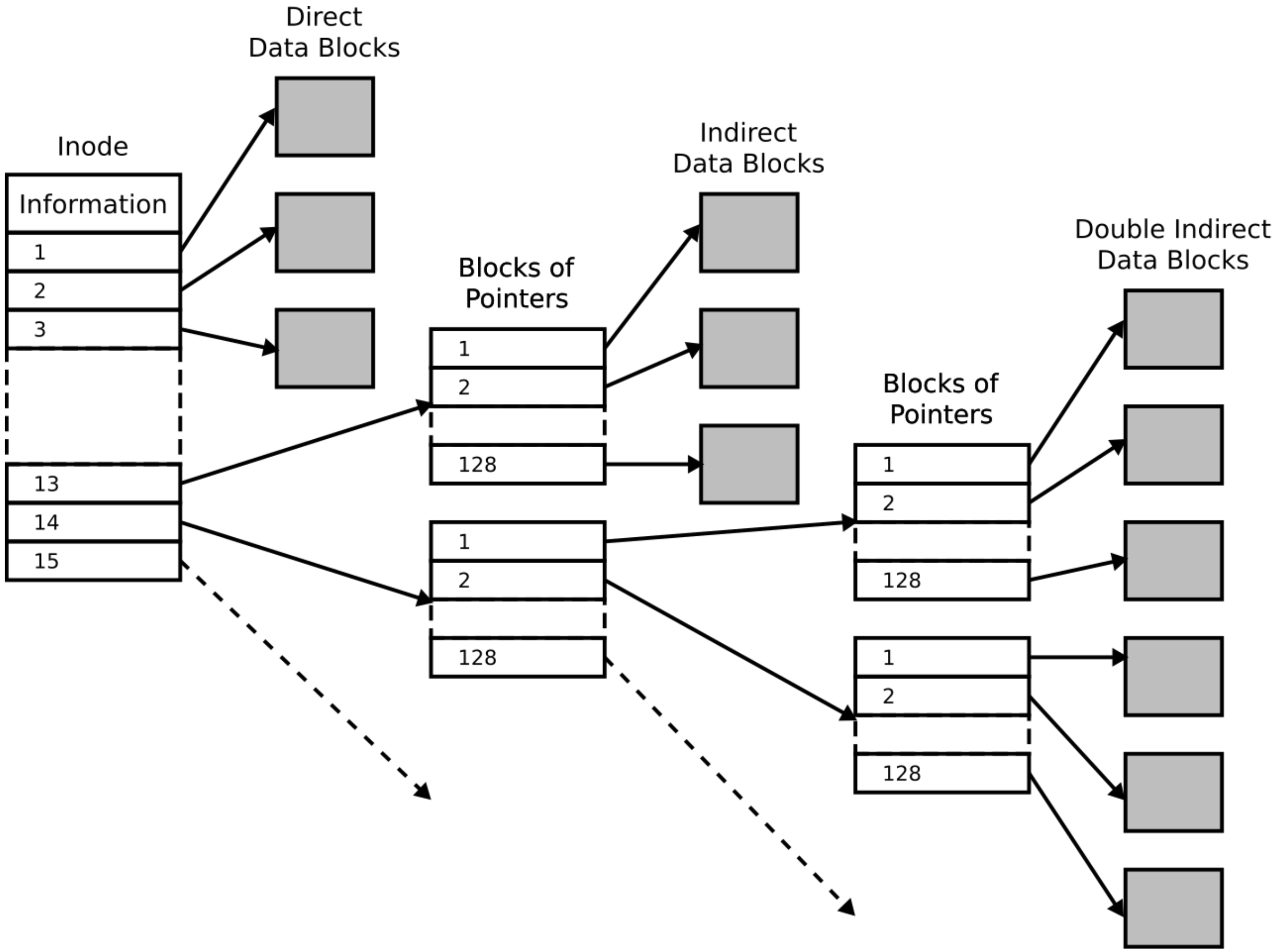
- Method: instead of over-writing existing data block
    - Write update to a brand new data block
    - Create a new inode for the file that points to the new data block
        - And still points to original data for the other unmodified blocks
    - New inode points to new version of file
    - Old inode points to old version of file

- No longer needs journal for correctness

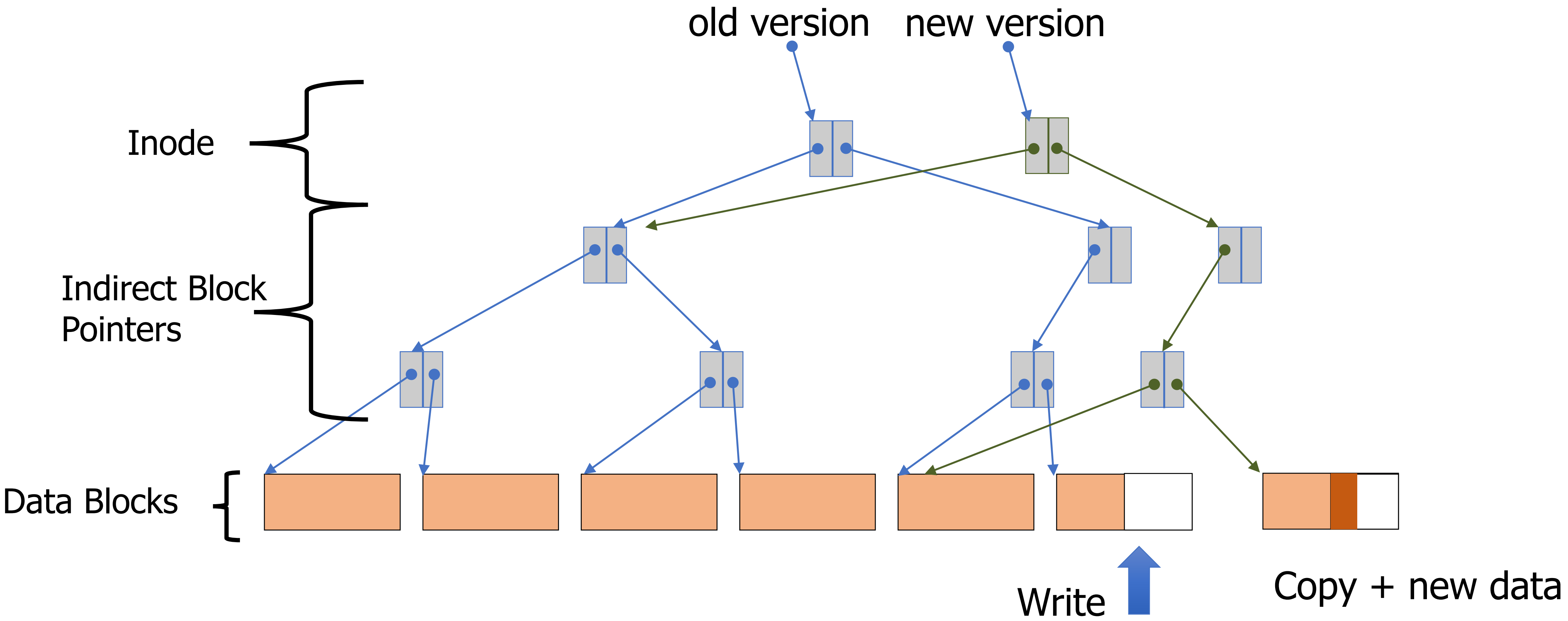
Reminder: hierarchical inodes

- Some bit in each entry specifies whether it points at:
  1. A data block
  2. A block with additional data pointers

- This system can recurse multiple layers deep
  - Allows for really large files



Copy-on-write example



old version

new version

Inode

Indirect Block Pointers

Data Blocks

Write

Copy + new data

ZFS

- Developed by Sun Microsystems, now Oracle (2006)

- Uses Copy-on-Write transactions

- Snapshots
  - Enabled by copy-on-write
  - Points in time for the filesystem can be “snapshot”
  - Files can be returned to prior versions from the snapshot

Pooled file system

- ZFS (and other filesystems) use a concept of pools of storage
    - Flips around disk-filesystem relationship
    - Instead of one filesystem per partition and multiple partitions per disk
    - One filesystem manages multiple disks

- Replaces need for RAID by allowing filesystem to make choices

- Common design pattern in computer systems
    - Abstractions make systems easy to use
    - Breaking abstractions allows for improved performance

Log-Structured File Systems

- Can go further along copy-on-write path
  - Entire disk is just a log of updates to files and inodes

- No longer doing small writes all over disk
  - Jumping between inodes and data blocks
  - Small, random writes are bad for HDD seek

- Instead, treat disk as a circular buffer that updates are written to
  - Write new data, then new inode after it, then next new data
  - All writes end up occurring sequentially
  - Garbage collect old file versions eventually when space gets low

Outline

- Disk Caching
- Classical Filesystems
    - FFS
    - FAT
- Improving Reliability
    - FSCK
    - Journaling
- Journaling Filesystems
    - ext3/ext4
    - NTFS
- Copy-On-Write
    - ZFS