Lecture 18: Filesystem Implementations

CS343 – Operating Systems

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Some slides borrowed from:
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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

Outline

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

Filesystem access results in a lot of disk interactions

	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					

time

update attributes

Many disk interactions should be hitting memory instead

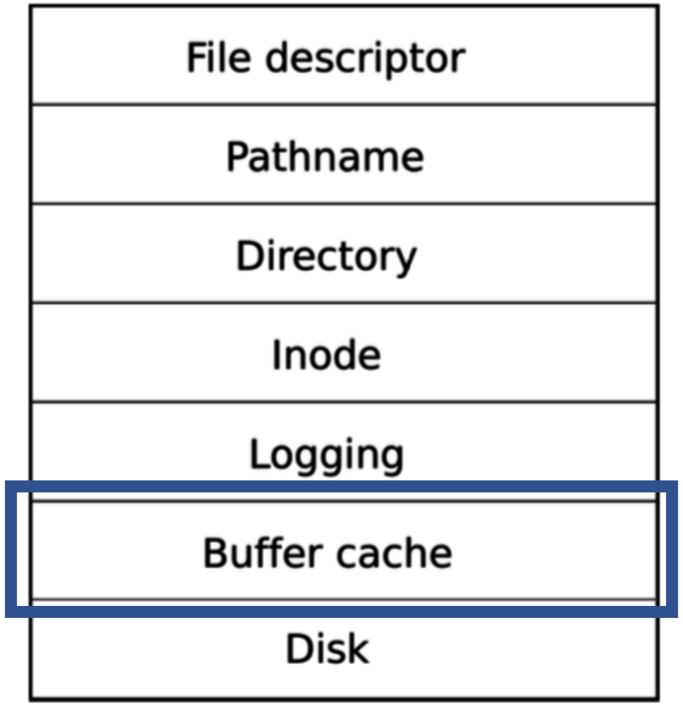
time

	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					

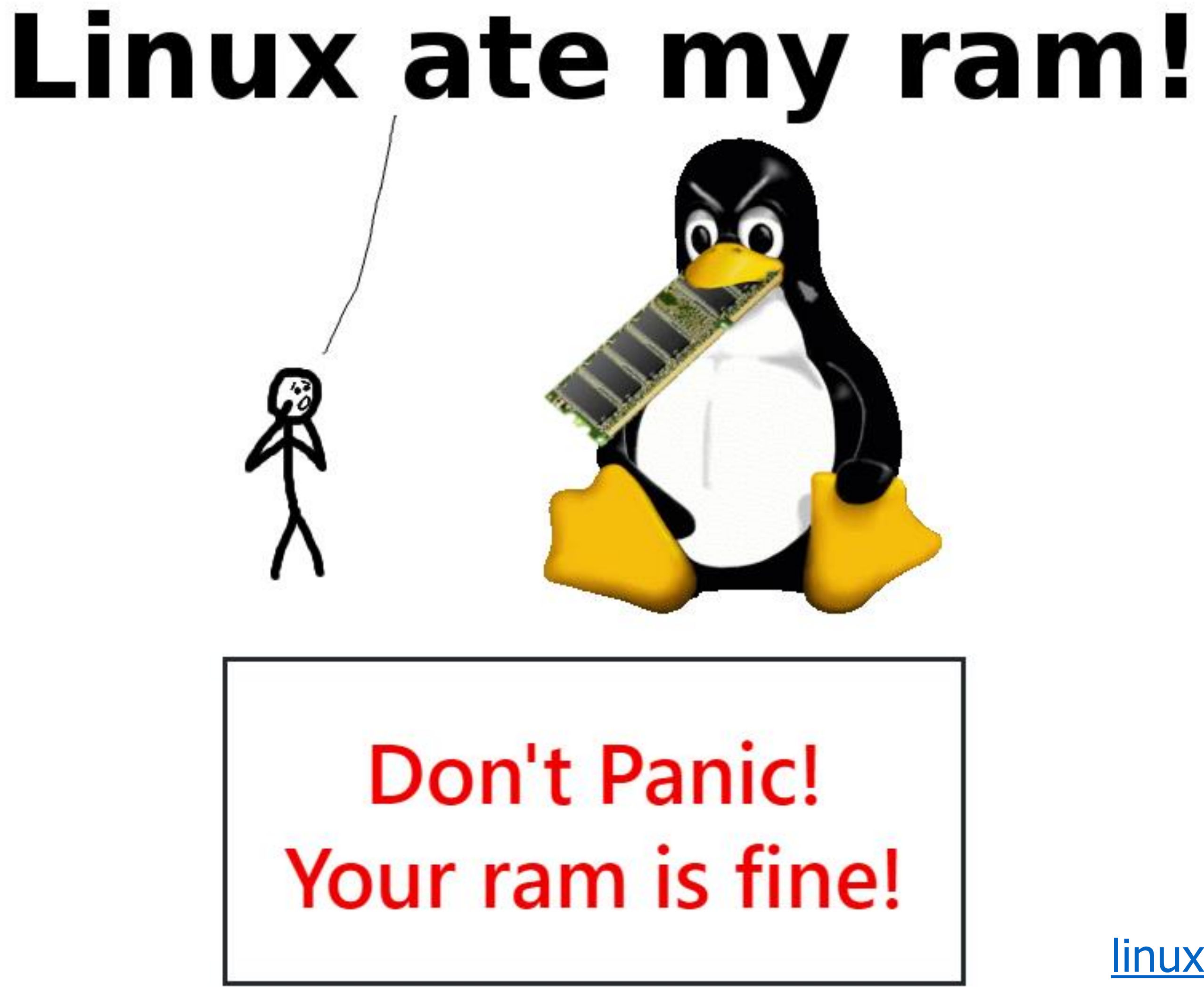
inode reads/writes
occur in memory

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



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

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
  1. Unwritten disk files or unmodified memory pages
     - Situational which is more important
  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

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

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
  - 16 byte granularity for files

FAT design choices

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

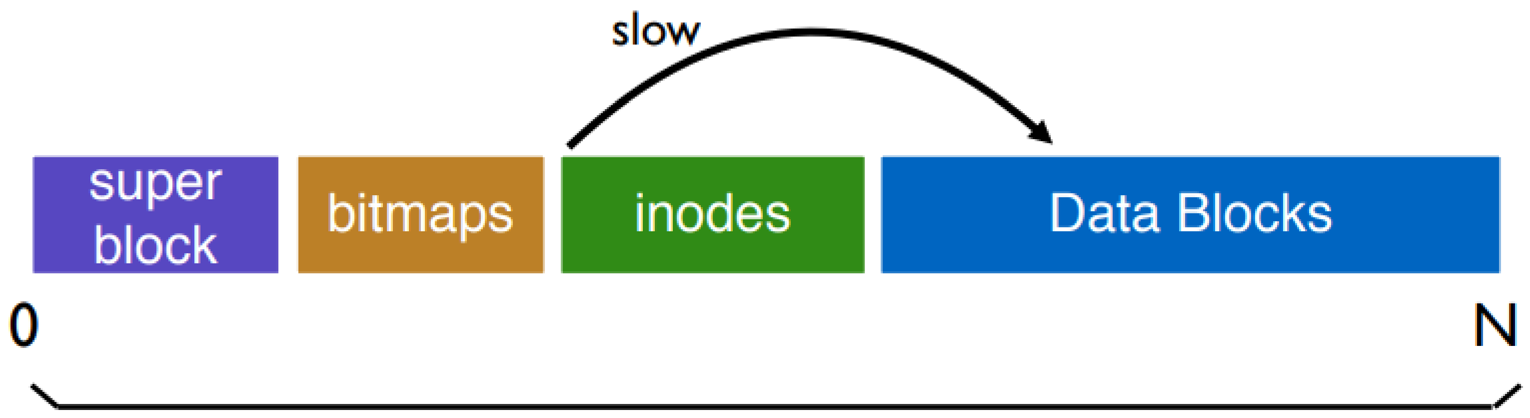
- Still in use for embedded systems
  - Simple to implement
  - Still compatible with modern general-purpose OSes
  - Works for small and relatively large files and disks
    - Think SD cards
  - Implements aggressive block caching

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

- 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

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  - **FSCK**
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- 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 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)

time	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]
					read			
	read							
write()	write							
								write
Crash here!								
					write			

- 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
  - Lost forever

- Other write order could be 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

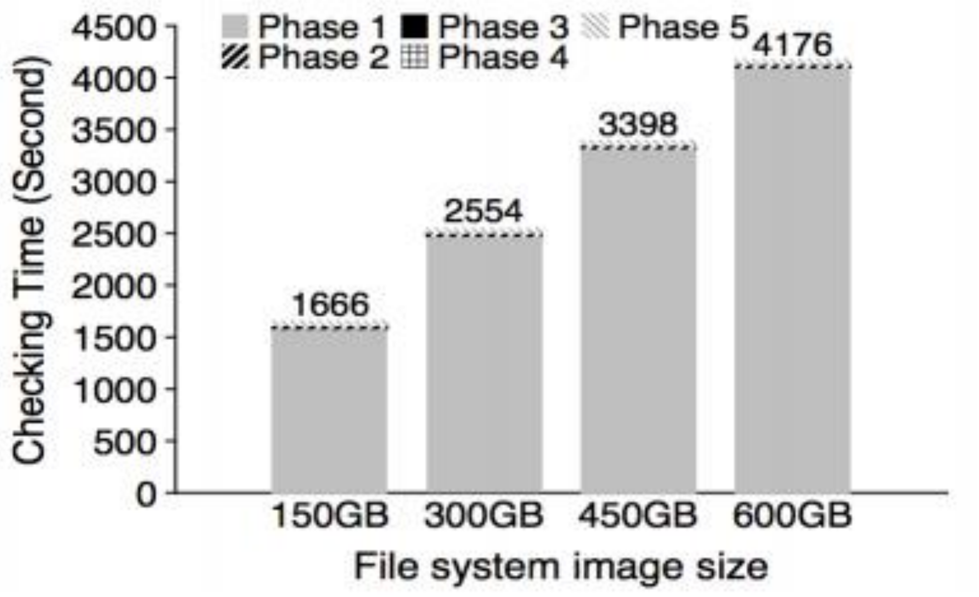
- Example: check data bitmap consistency
  - Read every valid inode
  - Any referenced data block should be marked as used
  - Any used blocks that are not referenced can be marked free

- 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

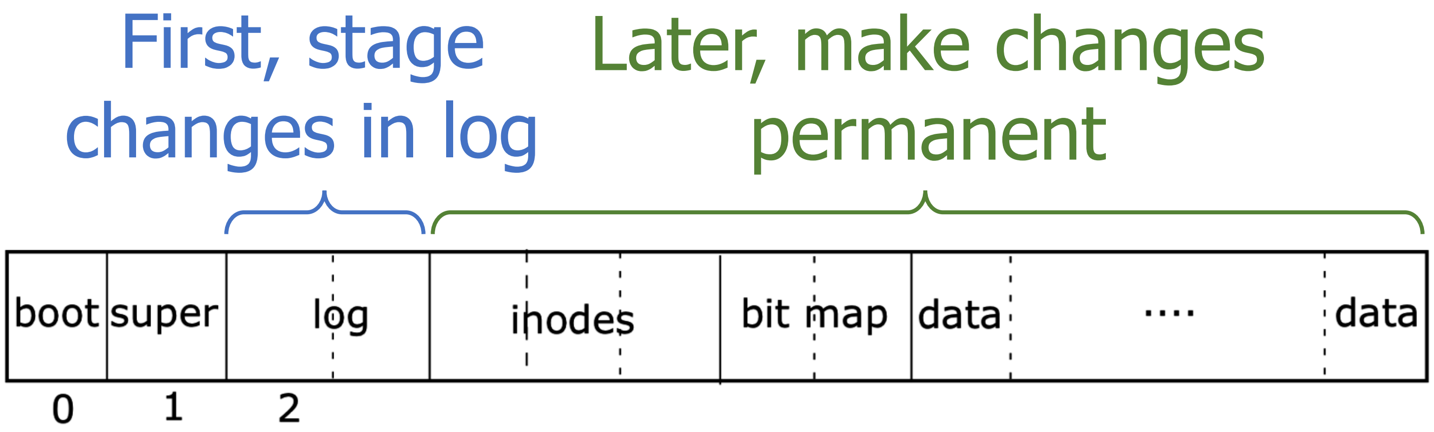
Filesystem transactions

- 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

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

- Write transaction start to journal

Journaling example

Journal

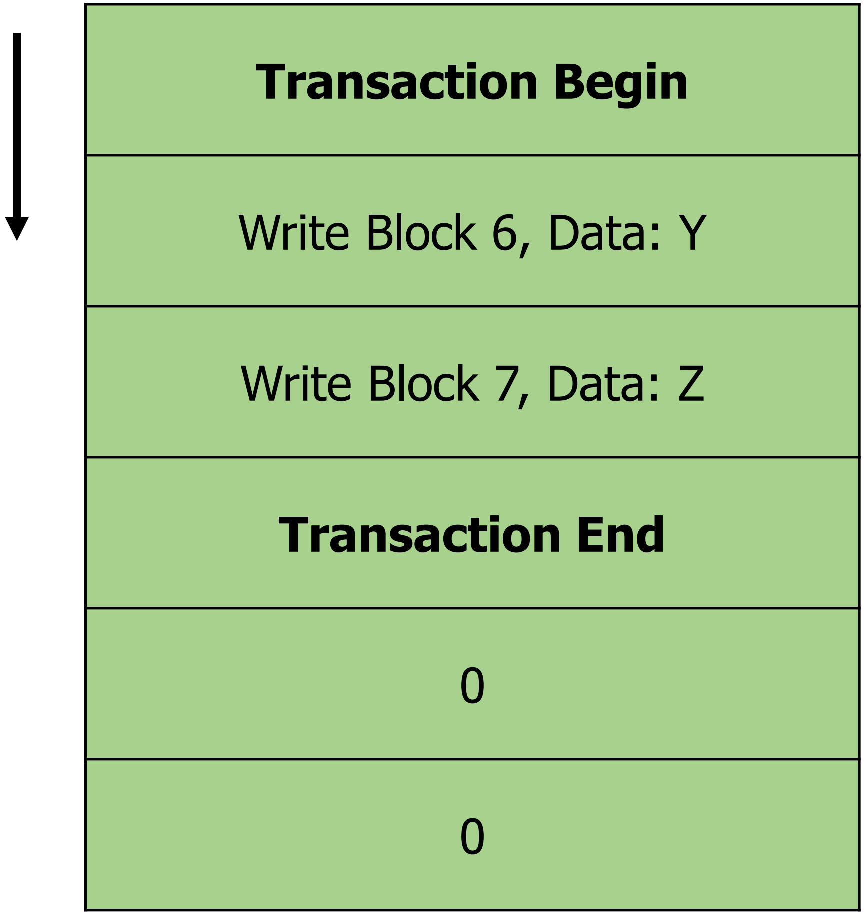
Transaction Begin
Write Block 6, Data: Y
Write Block 7, Data: Z
0
0
0

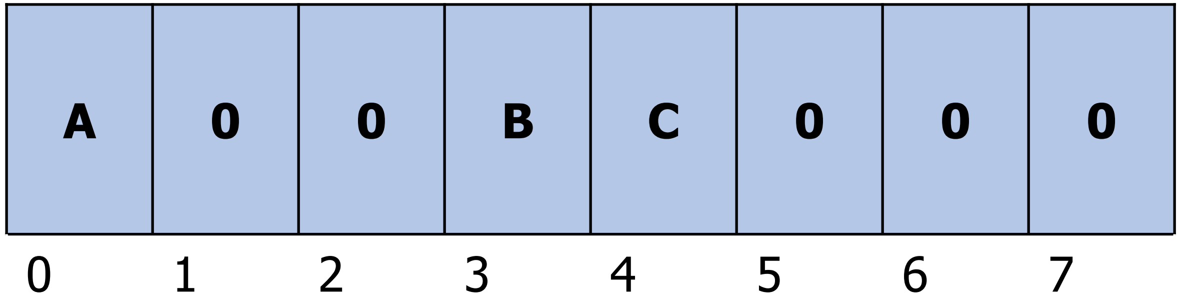
A	**0**	**0**	**B**	**C**	**0**	**0**	**0**
0	1	2	3	4	5	6	7

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

Journaling example

Journal





- 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

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

- Sometime after transaction is written, data can 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 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 transcractions 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.

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

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

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

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

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

- When did this crash occur?
  - After commit
  - Some data may have even been written (impossible to know)

- What step should be taken?
  - Replay transaction and perform the writes

Check your understanding – resolve after crash again

Journal

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

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

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

Check your understanding – resolve after crash again

Journal

0
0
0
0
0
0

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

- When did this crash occur?
  - Before transaction committed
- What step 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

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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 for 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

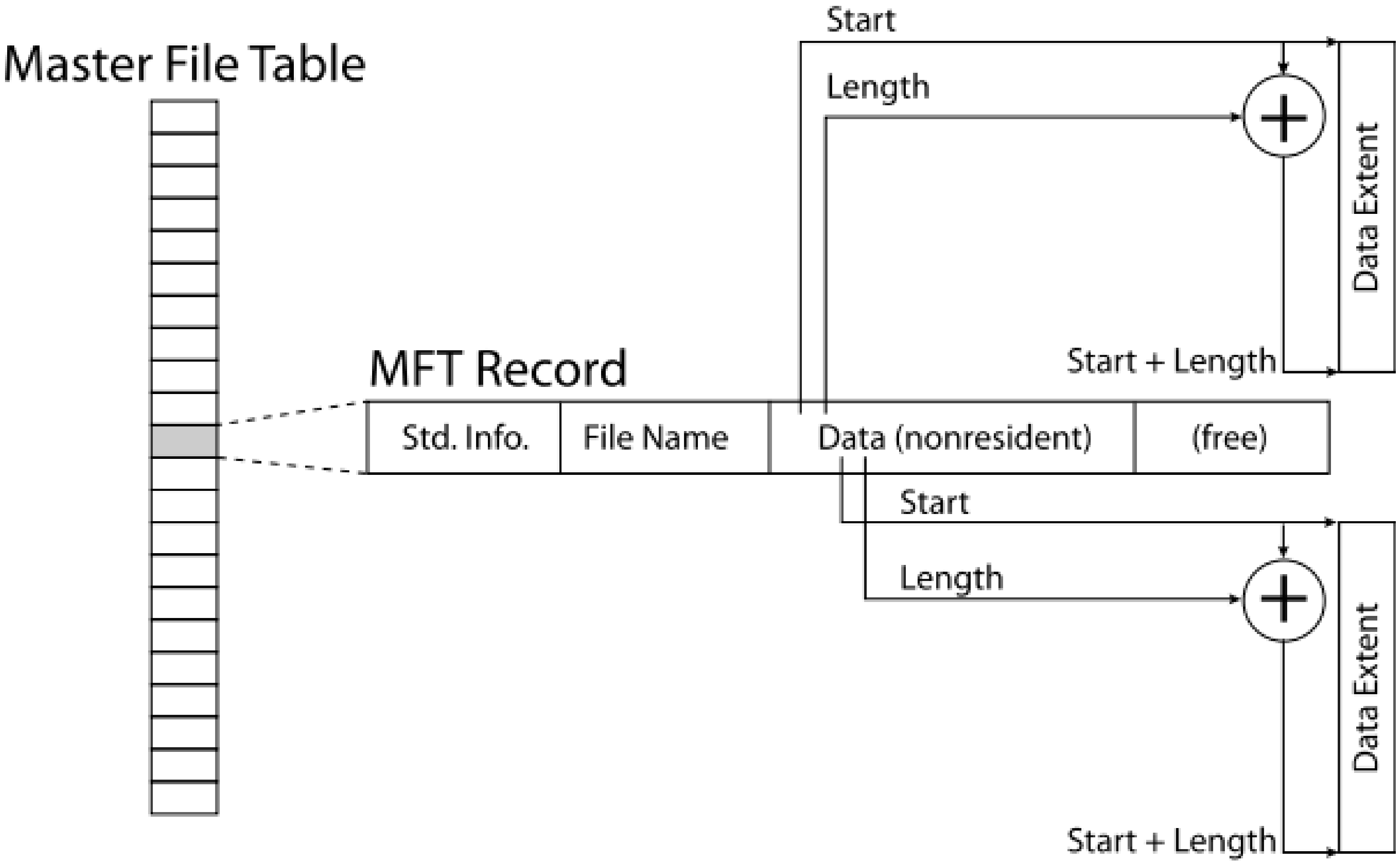
- Adds compression

NTFS Master File Table

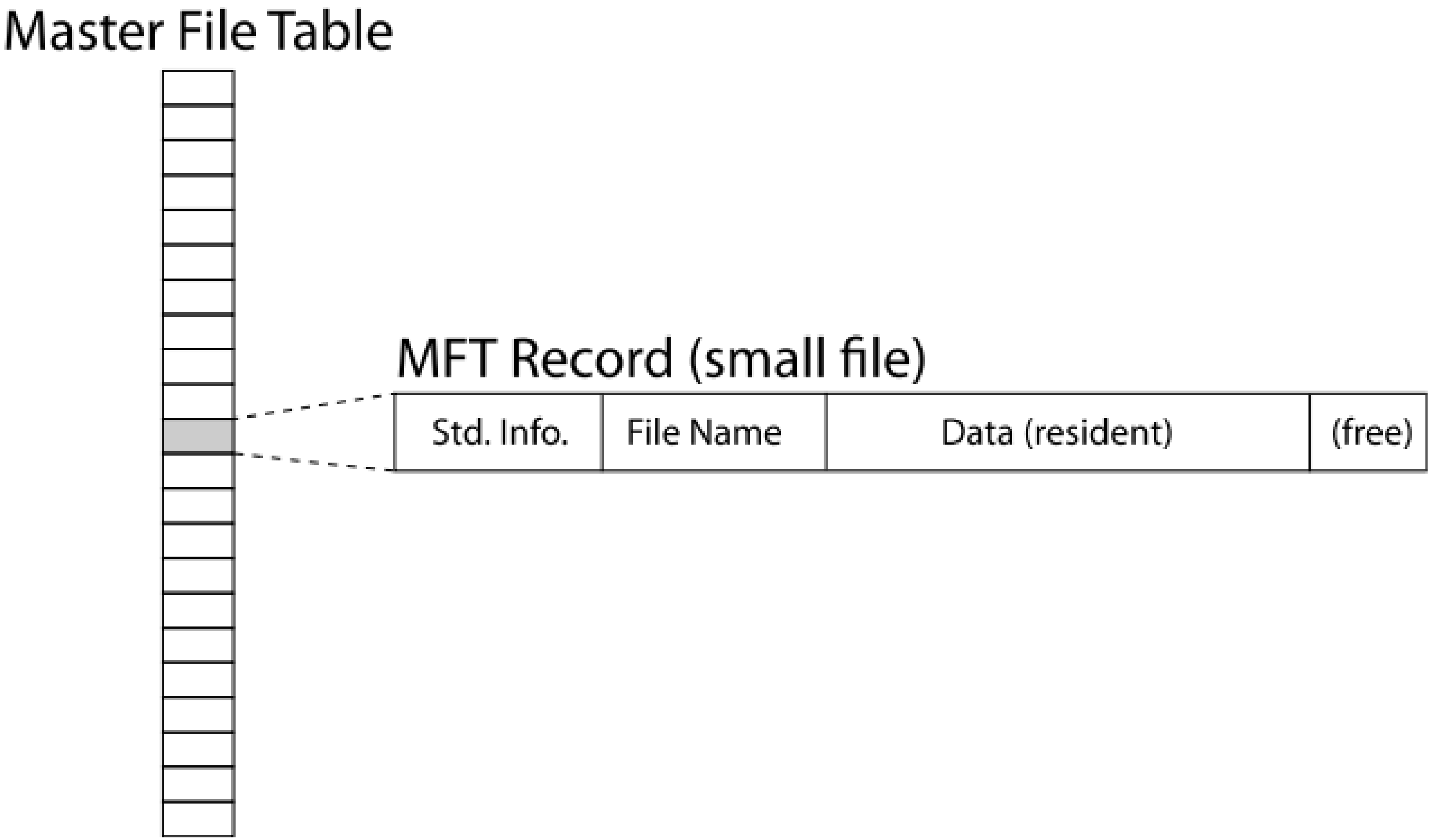
- Master File Table
  - Similar in practice to an array of inodes
  - Except that a single file can claim multiple MFT records
    - Additional records are indirected additional data block pointers

- 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 blocks)
    - Can hold file data itself!! (if small enough)

NTFS with medium-sized, 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

- In Windows 10, a service compresses infrequently used files
  - Unfortunately, can't compress already compressed files like videos and music

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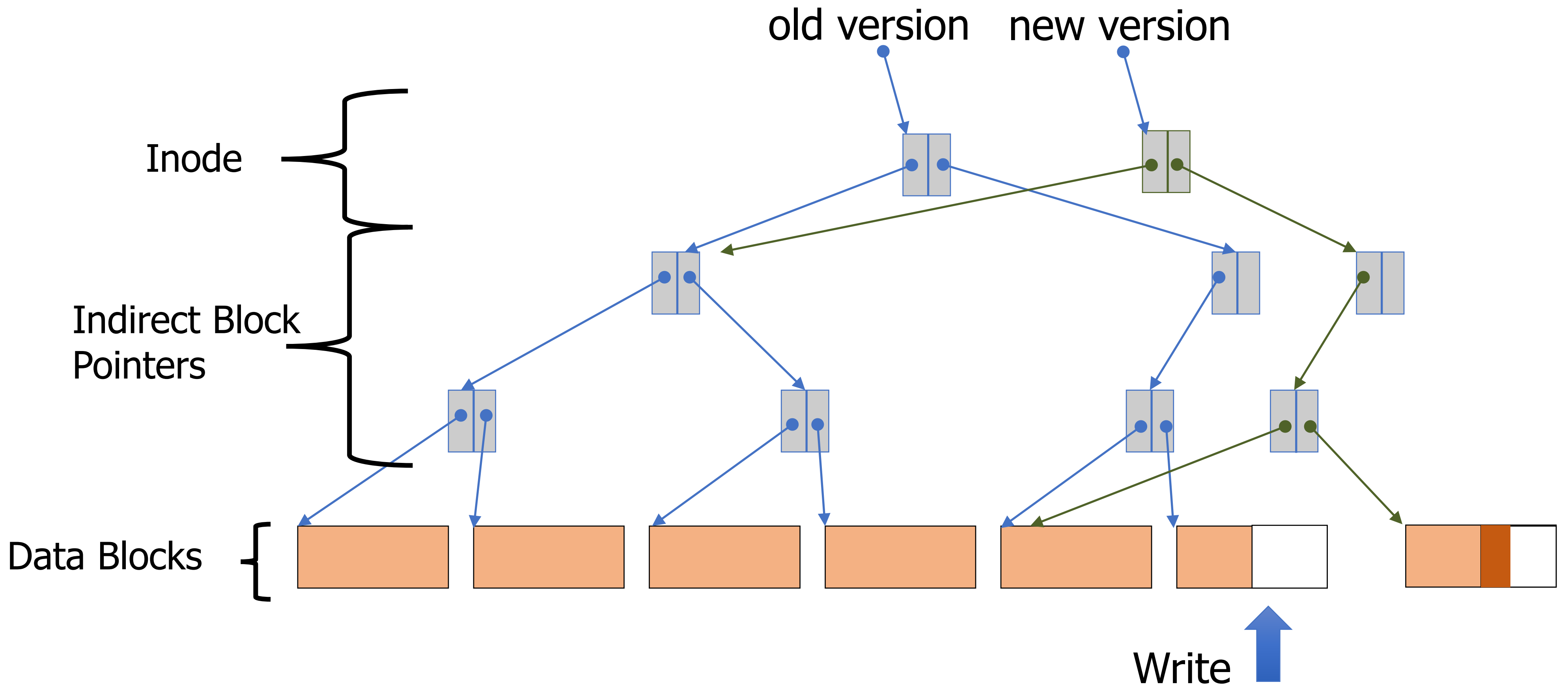
  - **ZFS**

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

Copy-on-write example



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

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