CS 318 Principles of Operating Systems

Fall 2017

Lecture 16: File Systems Examples

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File Systems Examples

- **BSD Fast File System (FFS)**
  - What were the problems with the original Unix FS?
  - How did FFS solve these problems?
- **Log-Structured File system (LFS)**
  - What was the motivation of LFS?
  - How did LFS work?

Original Unix FS

- **From Bell Labs by Ken Thompson**
- **Simple and elegant:**

Unix disk layout

- **Components**
  - Data blocks
  - Inodes (directories represented as files)
  - Free list
  - Superblock. (specifies number of blks in FS, counts of max # of files, pointer to head of free list)
- **Problem: slow**
  - Only gets 2% of disk maximum (20Kb/sec) even for sequential disk transfers!

Why So Slow?

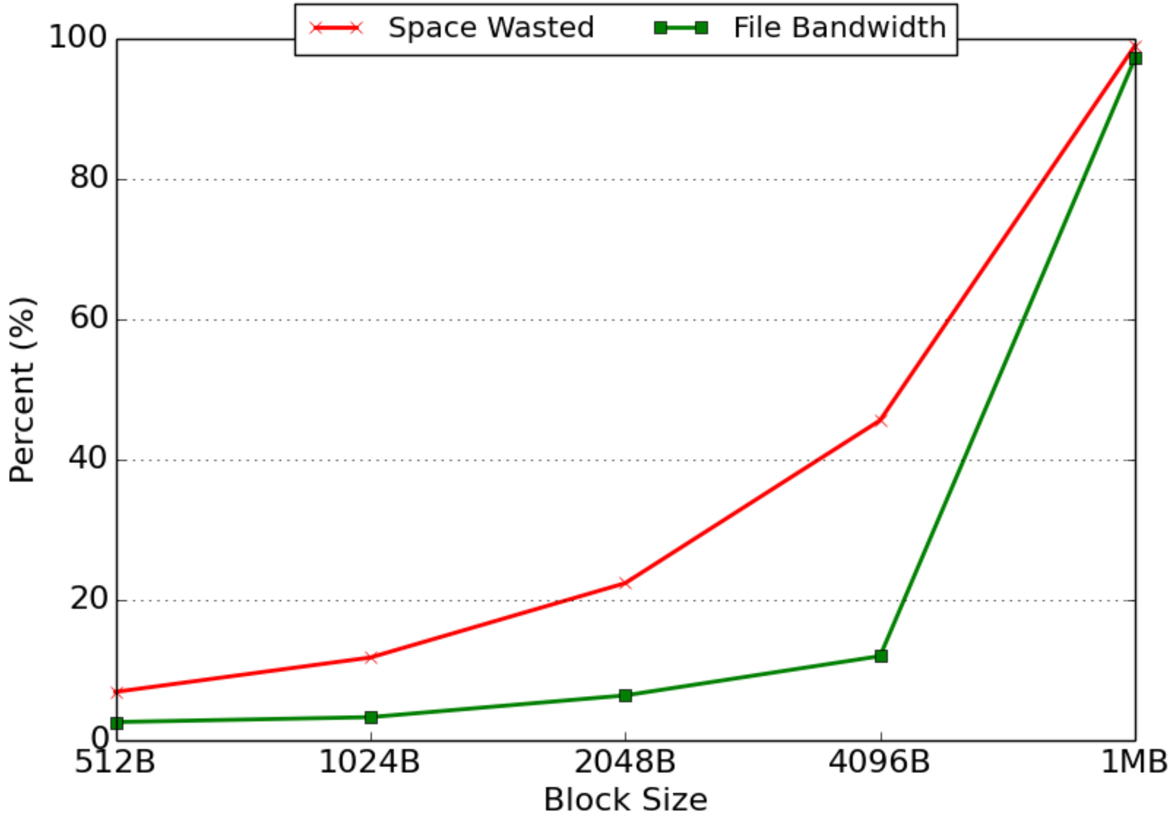
- **Problem 1: blocks too small (512 bytes)**
  - File index too large
  - Require more indirect blocks
  - Transfer rate low (get one block at time)
- **Problem 2: unorganized freelist**
  - Consecutive file blocks not close together
    - Pay seek cost for even sequential acces
  - Aging: becomes fragmented over time
- **Problem 3: poor locality**
  - inodes far from data blocks
  - inodes for directory not close together
    - poor enumeration performance: e.g., “ls”, “grep foo *.c”

FFS: Fast File System

- **Designed by a Berkeley research group for the BSD UNIX**
  - A classic file systems paper to read: [McKusic]
- **Approach:**
  - measure an state of the art systems
  - identify and understand the fundamental problems
    - The original FS treats disks like random-access memory!
  - get an idea and build a better systems
- **Idea: design FS structures and allocation polices to be "disk aware"**
- **Next: how FFS fixes the performance problems (to a degree)**

Problem 1: Blocks Too Small

Measurement:



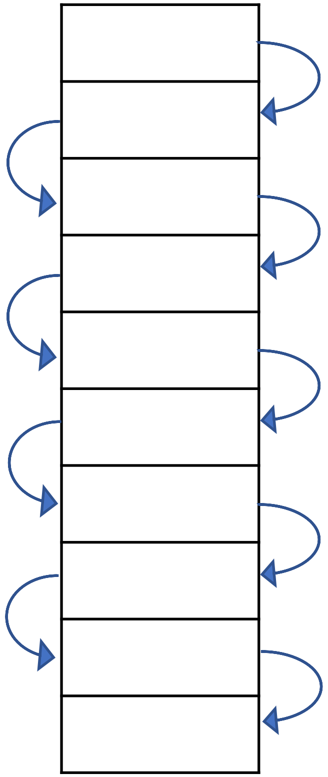
- **Bigger block increases bandwidth, but how to deal with wastage ("internal fragmentation")?**
  - Use idea from malloc: split unused portion

Solution: Fragments

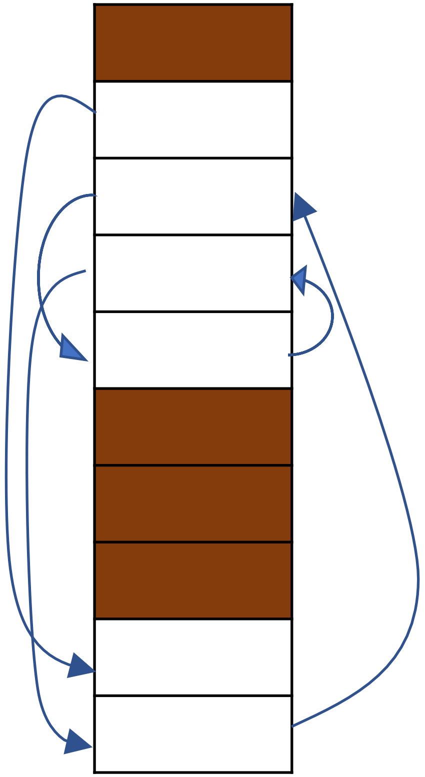
- **BSD FFS:**
  - Has large block size (4096B or 8192B)
  - Allow large blocks to be chopped into small ones called “fragments”
    - Fragment size specified at the time that the file system is created
    - Algorithm to ensure fragments only used for little files or ends of files
    - Limit number of fragments per block to 2, 4, or 8
    - Keep track of free fragments
- **Pros**
  - High transfer speed for larger files
  - Low wasted space for small files or ends of files

Problem 2: Unorganized Freelist

- **Leads to random allocation of sequential file blocks overtime**



Initial performance good



Get worse over time

Measurement:

- New FS: **17.5%** of disk bandwidth
- Few weeks old: **3%** of disk bandwidth

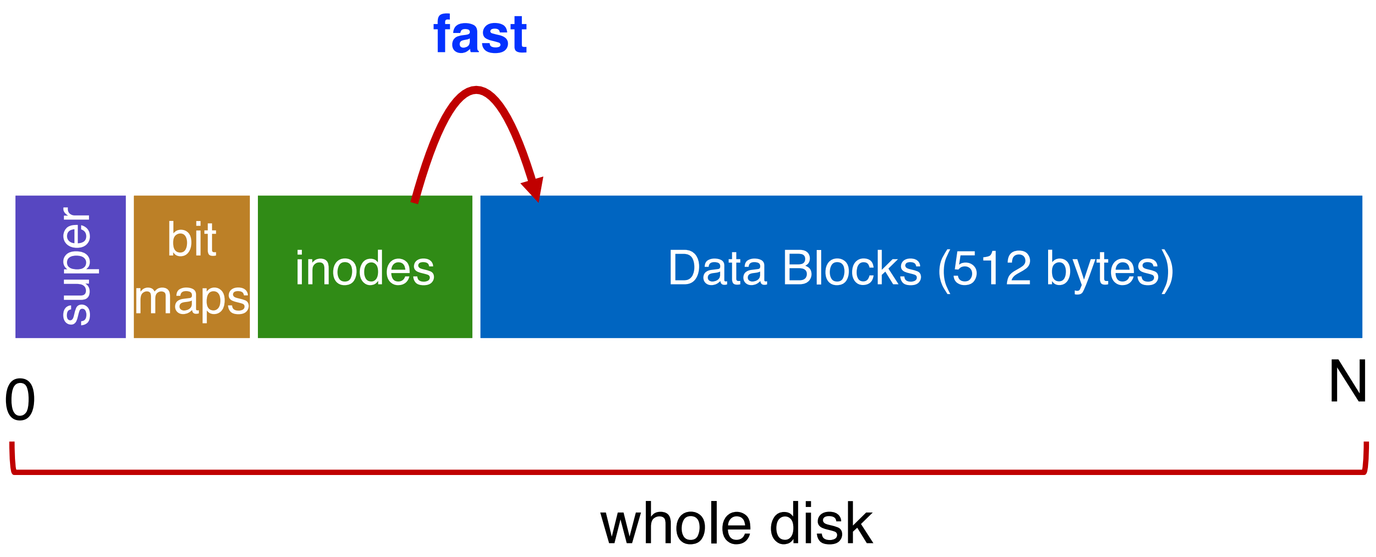
Fixing the Unorganized Freelist

- **Periodical compact/defragment disk**
  - Cons: locks up disk bandwidth during operation
- **Keep adjacent free blocks together on freelist**
  - Cons: costly to maintain
- **FFS: bitmap of free blocks**
  - Each bit indicates whether block is free
    - E.g., 1010101111111000001111111000101100
  - Easier to find contiguous blocks
  - Small, so usually keep entire thing in memory
  - Time to find free blocks increases if fewer free blocks

Using a Bitmap

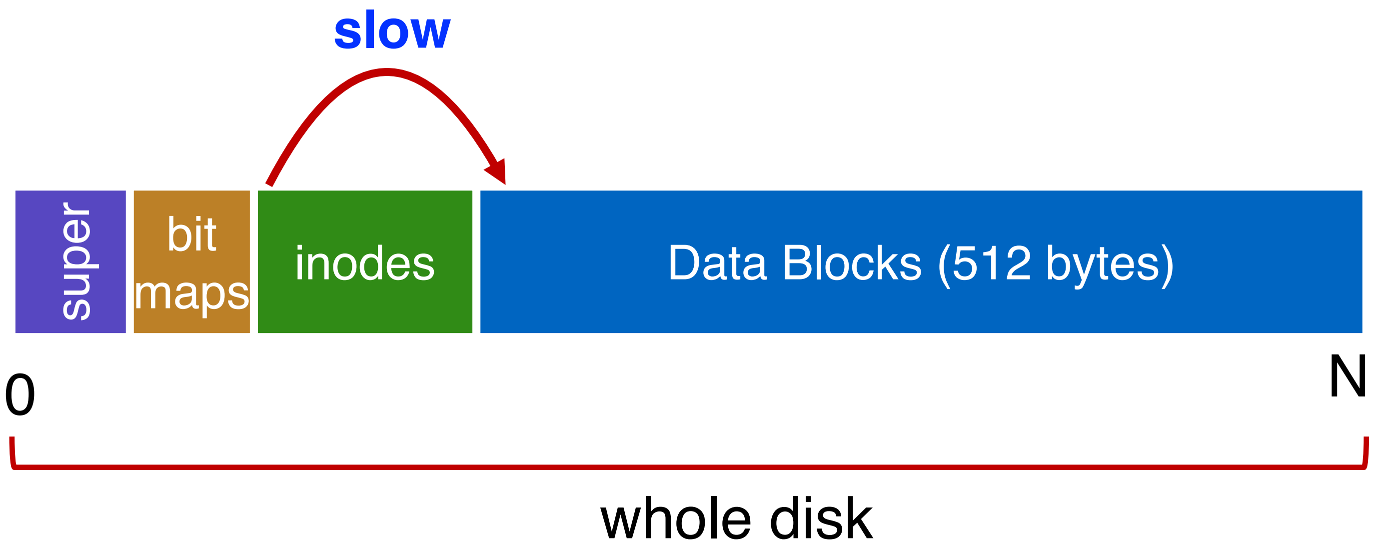
- **Usually keep entire bitmap in memory:**
  - 4G disk / 4K byte blocks. How big is map?
- **Allocate block close to block x?**
  - Check for blocks near bmap[x/32]
  - If disk almost empty, will likely find one near
  - As disk becomes full, search becomes more expensive and less effective
- **Trade space for time (search time, file access time)**

Problem 3: Poor Locality



- **How to keep inode close to data block?**

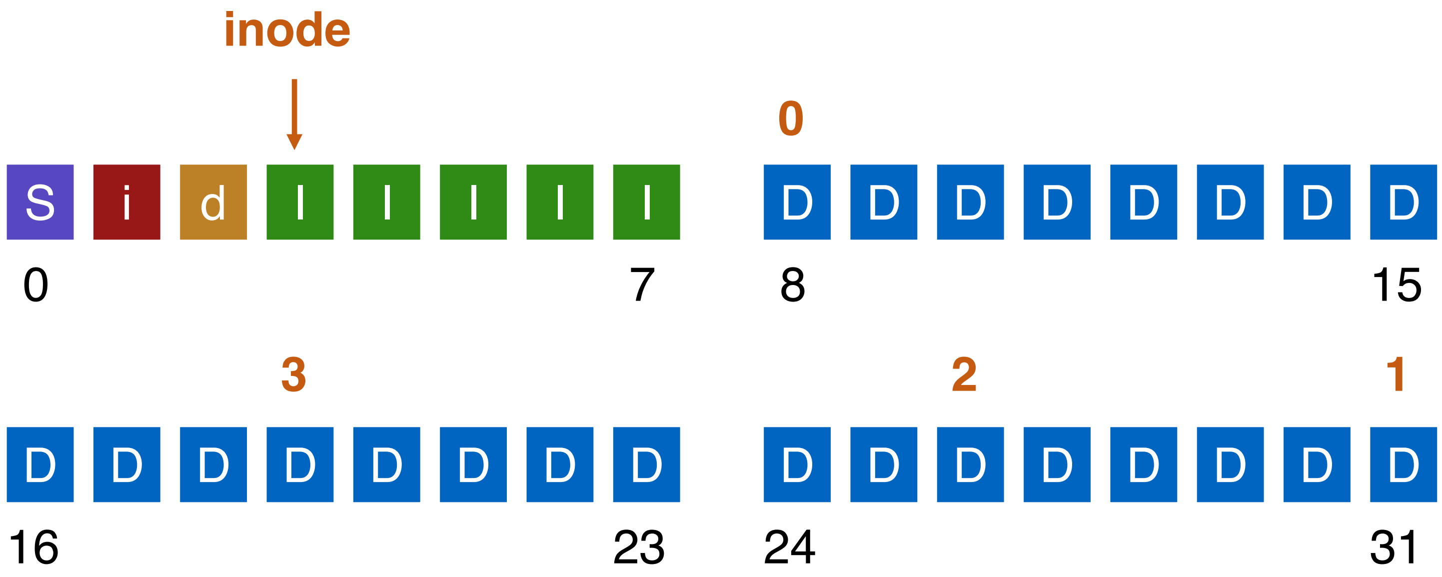
Problem 3: Poor Locality



- **How to keep inode close to data block?**

Problem 3: Poor Locality

- **Example bad layout:**



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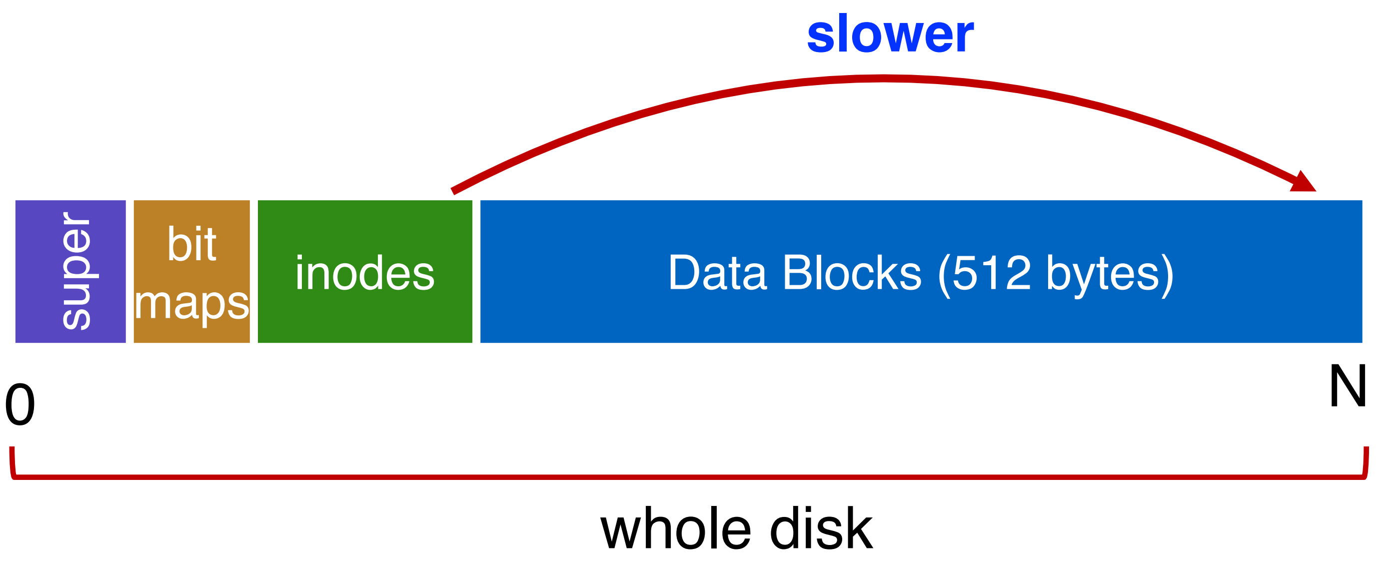
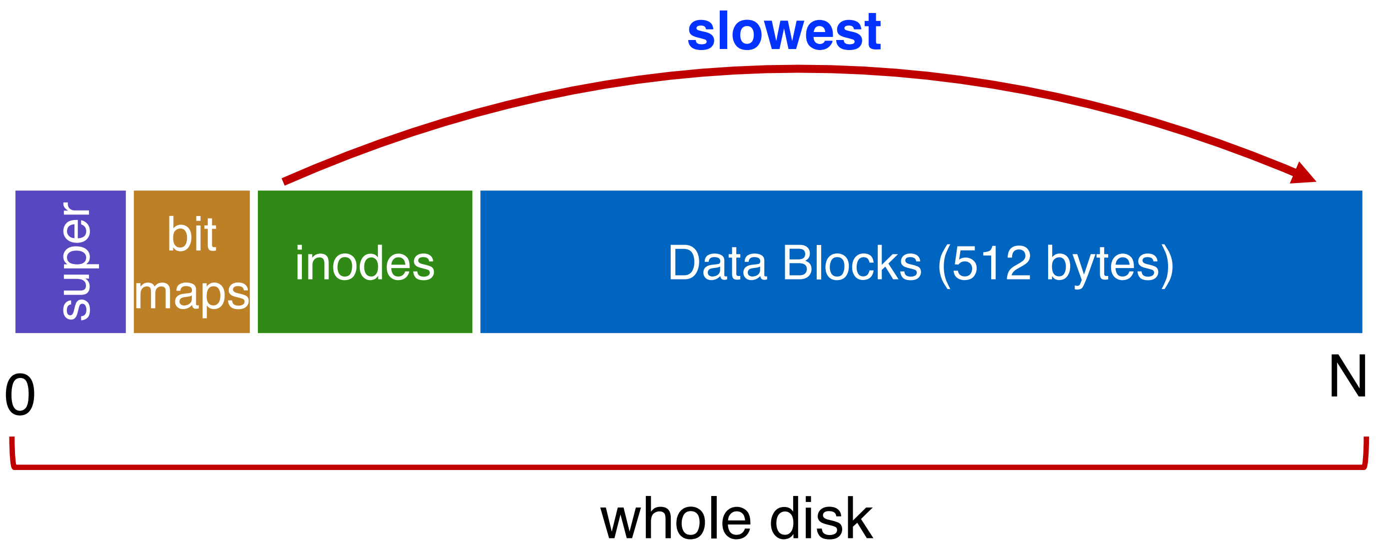
Problem 3: Poor Locality



- **How to keep inode close to data block?**

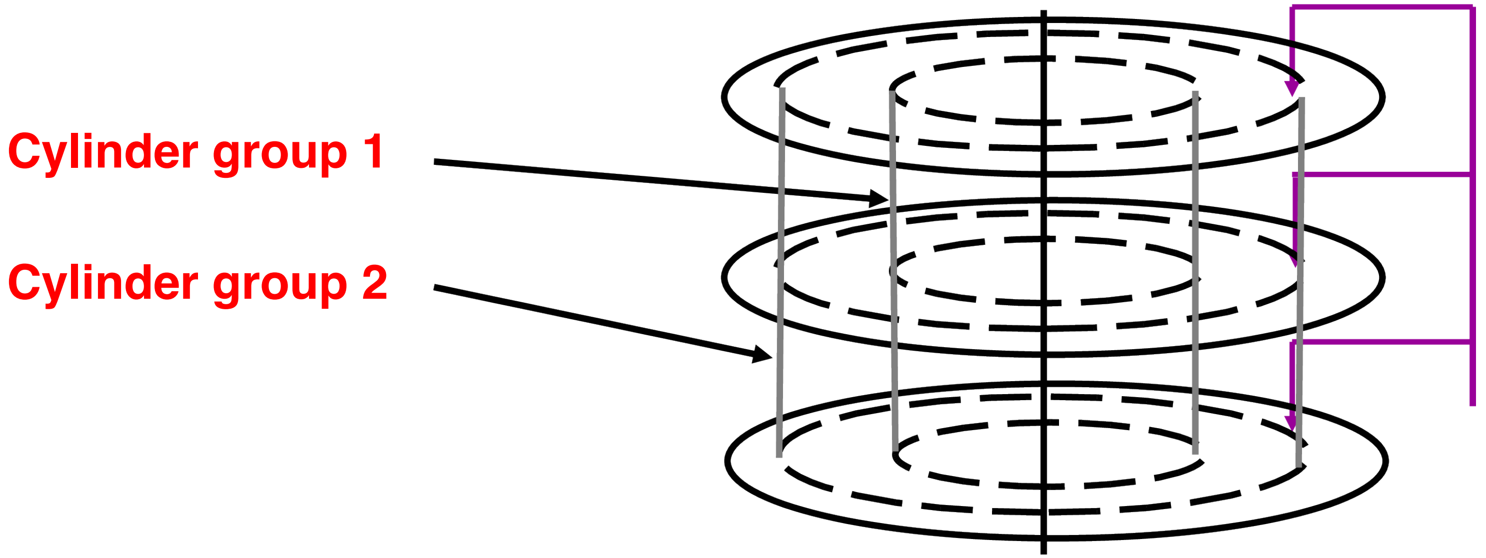
Problem 3: Poor Locality



- **How to keep inode close to data block?**

FFS Solution: Cylinder Group

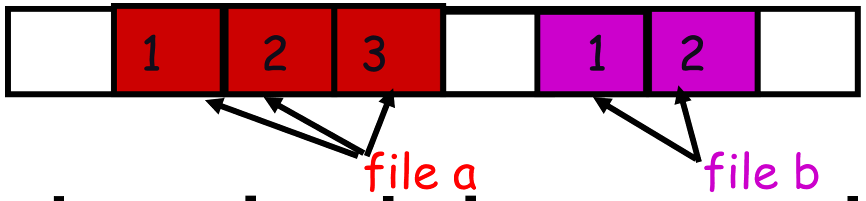
- **Group sets of consecutive cylinders into “cylinder groups”**



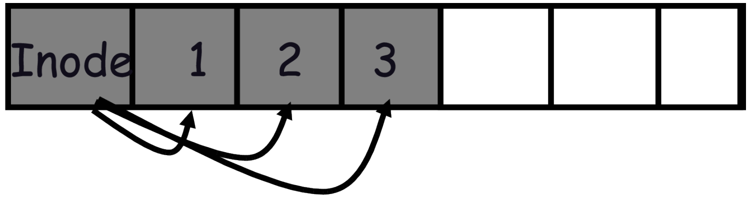
  - Key: can access any block in a cylinder without performing a seek. Next fastest place is adjacent cylinder.
  - Tries to put everything related in same cylinder group
  - Tries to put everything not related in different group

Clustering in FFS

- **Tries to put sequential blocks in adjacent sectors**
  - (Access one block, probably access next)

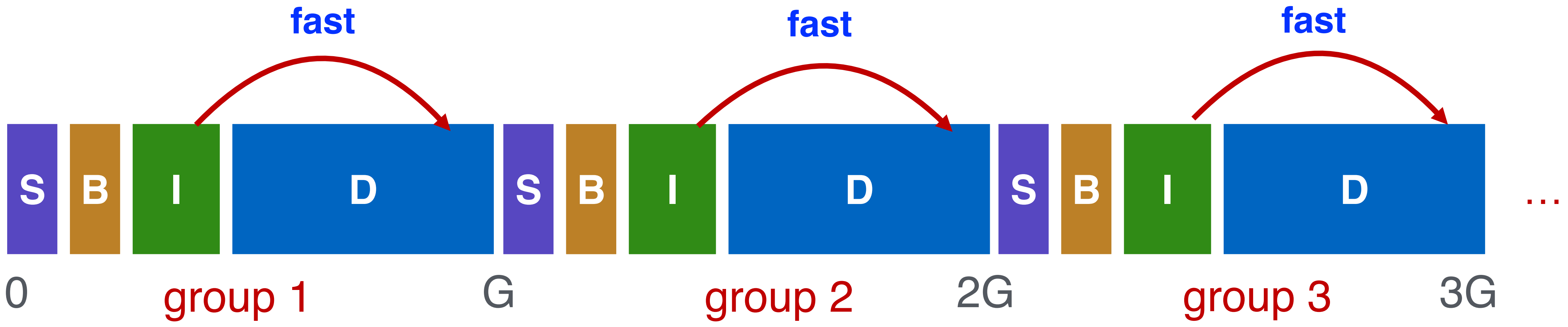


- **Tries to keep inode in same cylinder as file data:**
  - (If you look at inode, most likely will look at data too)



- **Tries to keep all inodes in a dir in same cylinder group**
  - Access one name, frequently access many, e.g., “ls -l”

What Does Disk Layout Look Like Now?



- **How to keep inode close to data block?**
  - Answer: Use groups across disks
  - Strategy: allocate inodes and data blocks in same group
  - Each cylinder group basically a mini-Unix file system
- **Is it useful to have multiple super blocks?**
  - Yes, if some (but not all) fail

FFS Results

- **Performance improvements:**
  - Able to get 20-40% of disk bandwidth for large files
  - 10-20x original Unix file system!
  - Stable over FS lifetime
  - Better small file performance (why?)
- **Other enhancements**
  - Long file names
  - Parameterization
  - Free space reserve (10%) that only admin can allocate blocks from

LFS: Log-structured File System

- **Motivation**
  - Faster CPUs: I/O becomes more and more of a bottleneck
  - More memory: file cache is effective for reads
  - Implication: writes compose most of disk traffic
- **Problems with previous FS**
  - Perform many small writes
    - Good performance on large, sequential writes, but many writes are still small, random
  - Synchronous operation to avoid data loss
  - Depends upon knowledge of disk geometry
- **An influential work designed by Mendel Rosenblum (VMWare co-founder) and John Ousterhout**

LFS Idea

- **Insight: treat disk like a tape-drive**
  - Best performance from disk for sequential access
- **File system buffers writes in main memory until "enough" data**
  - How much is enough?
  - Enough to get good sequential bandwidth from disk (MB)
  - Unit called a "segment"
- **Write buffered data to new segment on disk in a sequential log**
  - Transfer all updates into a series of sequential writes
  - Do not overwrite old data on disk: old copies left behind
  - Write both data and metadata in one operation

Pros And Cons

- **Pros**
  - Always large sequential writes → good performance
  - No knowledge of disk geometry
    - Assume sequential better than random
- **Potential problems**
  - How do you find data to read?
  - What happens to metadata during write?
  - What happens when you fill up the disk?

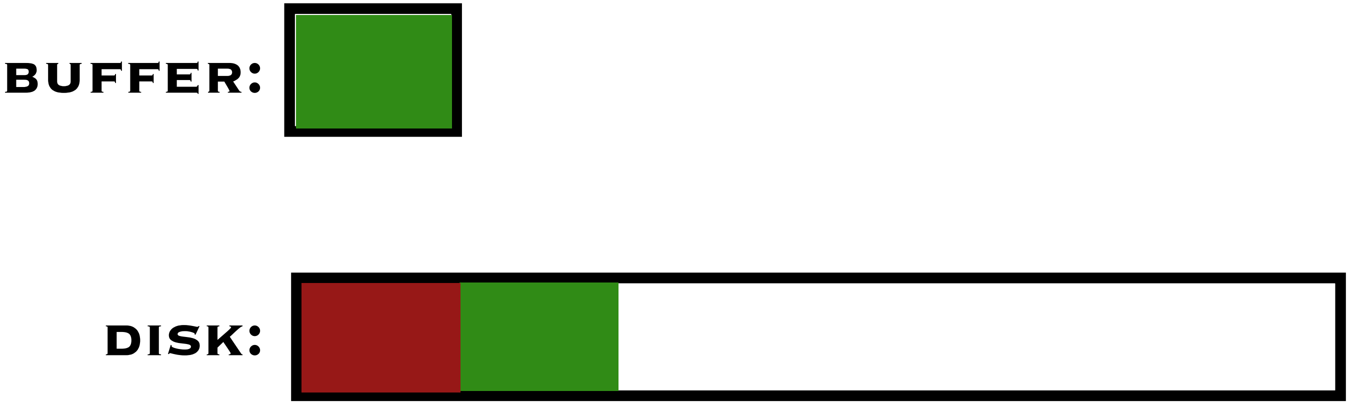
Read in LFS

- **Same basic structures as Unix**
  - Directories, inodes, indirect blocks, data blocks
  - Reading data block implies finding the file’s inode
    - Unix FS: inodes kept in array
    - LFS: inodes spread around on disk
- **Solution: inode map indicates where each inode is stored**
  - Can keep cached copy in memory
  - inode map written to log with everything else
  - Periodically written to known checkpoint location on disk for crash recovery

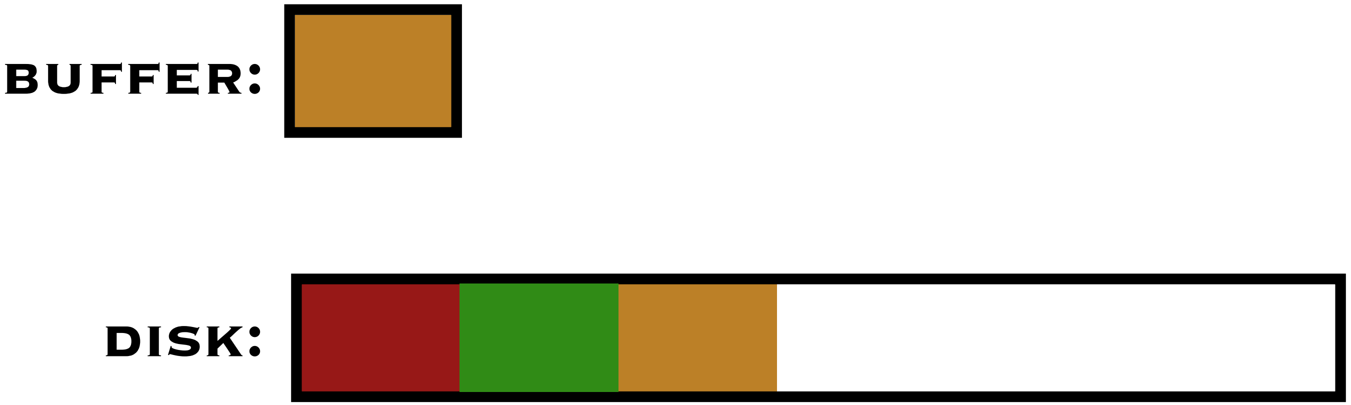
Write in LFS

- **Why do we buffer the write?**
  - Sequential write alone is not enough
  - Disk is constantly rotating!
  - Must issue a large number of contiguous writes

Write in LFS

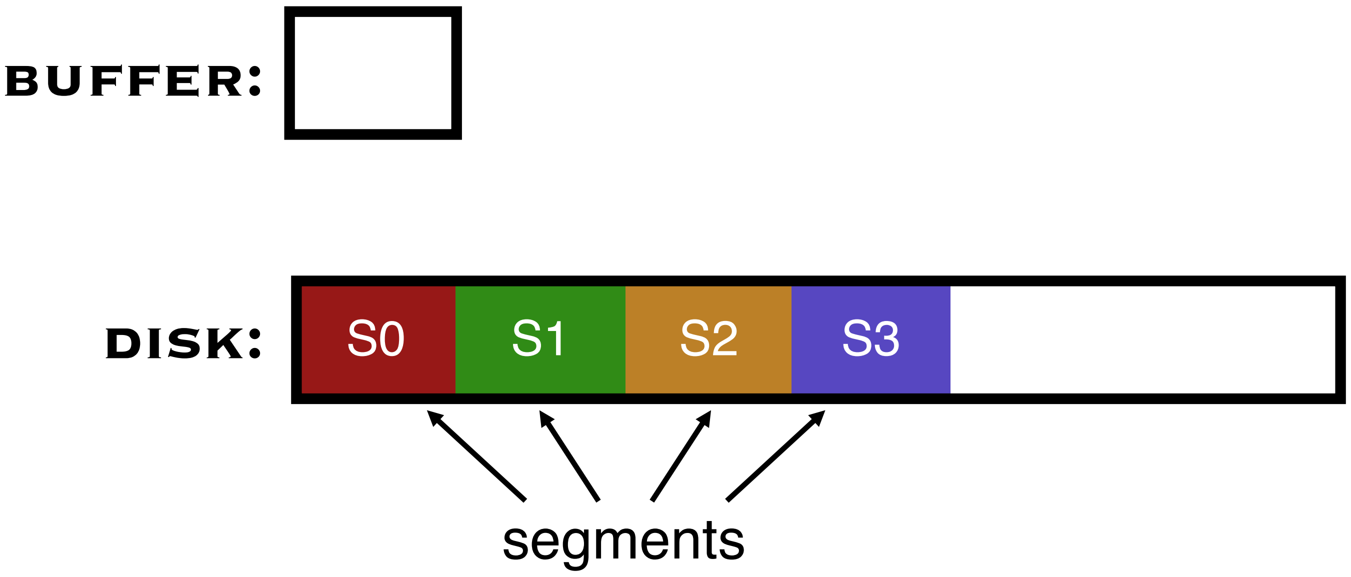


Write in LFS



Write in LFS

Write in LFS



Data Structures for LFS (attempt 1)

What data structures from FFS can LFS remove?

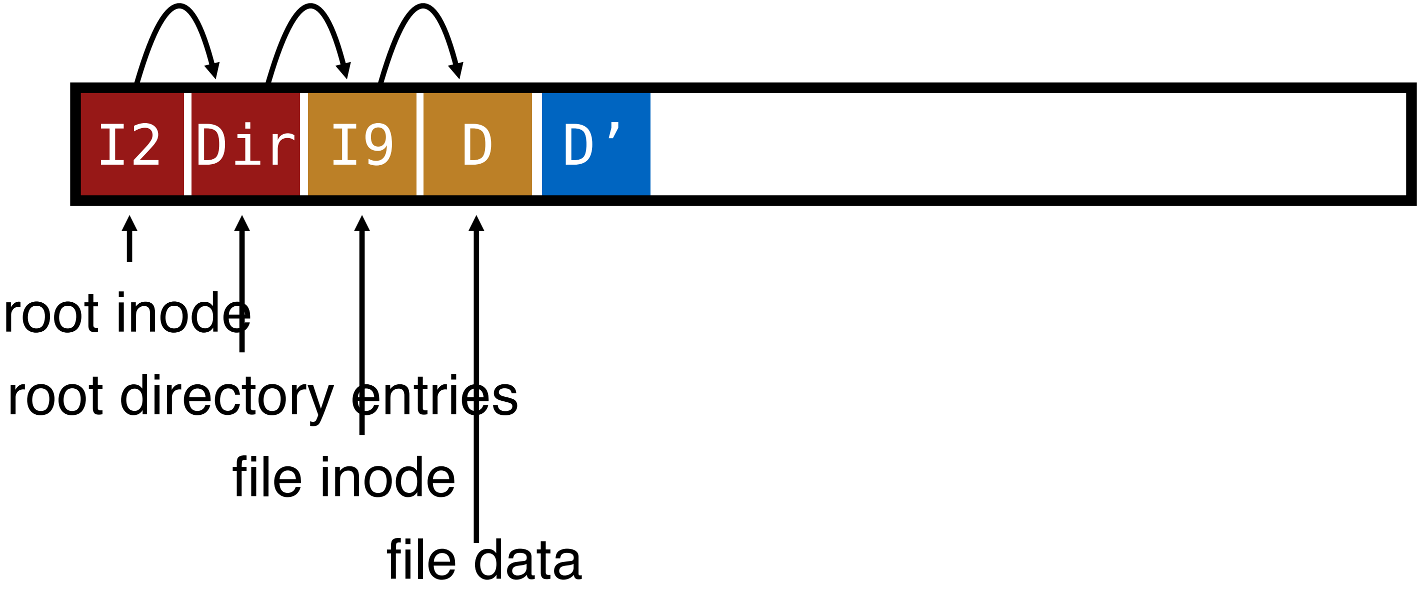
- allocation structs: data + inode bitmaps

What type of name is much more complicated?

- Inodes are no longer at fixed offset
- Use **current offset on disk** instead of table index for name
- Note: when update inode, inode number changes!!

Overwrite Data in LFS – Attempt 1

- **Overwrite data in /file.txt**



- **How to update Inode 9 to point to new D’ ???**

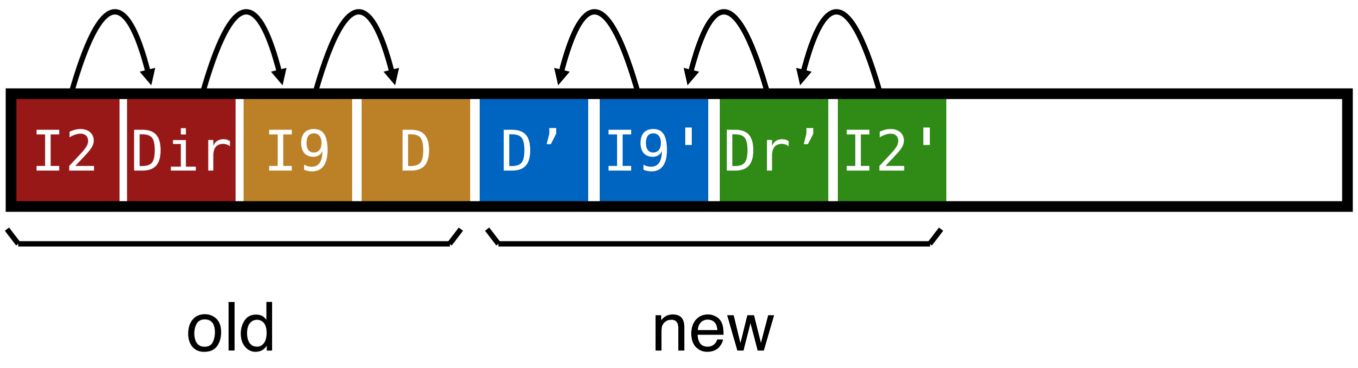
Overwrite Data in LFS – Attempt 1

- **Overwrite data in /file.txt**

- **Can LFS update Inode 9 to point to new D’?**
  - NO! This would be a random write

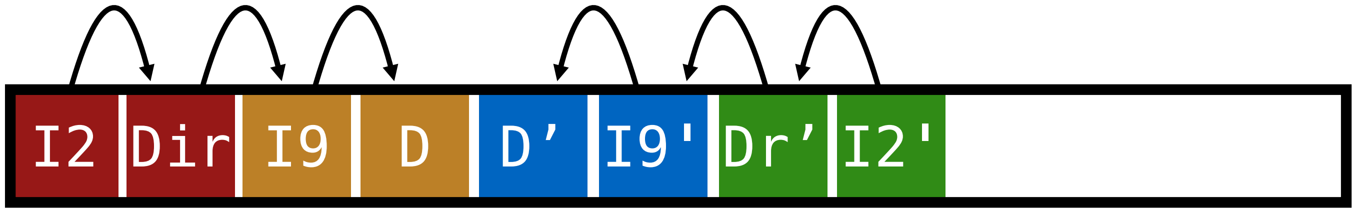
Overwrite Data in LFS – Attempt 1

- **Overwrite data in /file.txt**



- **Must update all structures in sequential order to log**

Attempt 1: Problem w/ Inode Numbers



- **Problem:**
  - For every data update, must propagate updates all the way up directory tree to root
- **Why?**
  - When inode copied, its location (inode number) changes
- **Solution:**
  - Keep inode numbers constant; don’t base name on offset
- **FFS found inodes with math. How now?**

Data Structures for LFS (attempt 2)

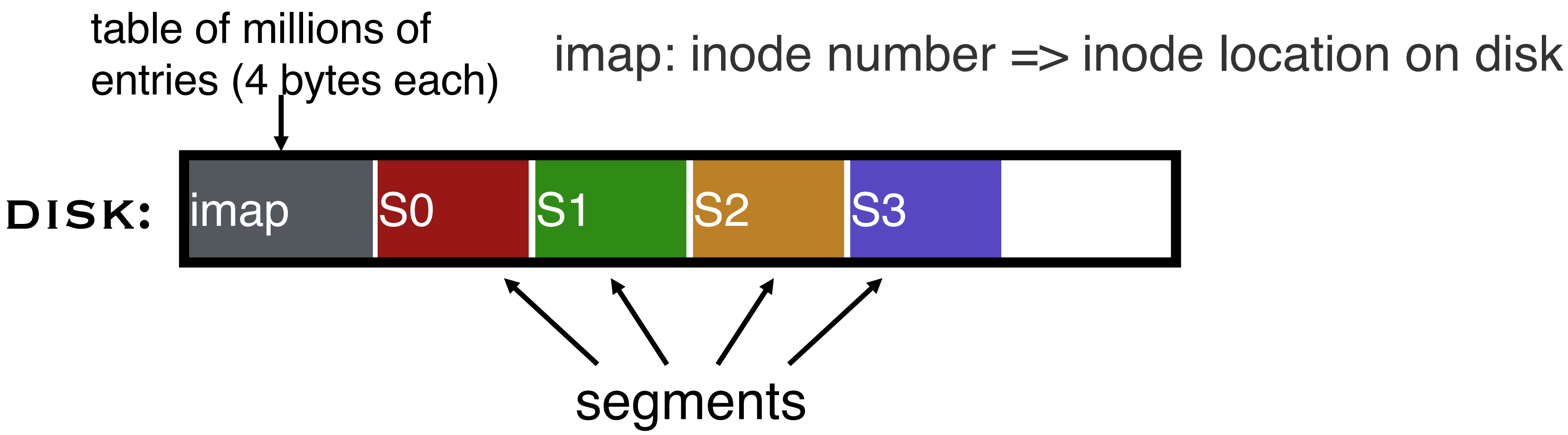
What data structures from FFS can LFS remove?

- allocation structs: data + inode bitmaps

What type of name is much more complicated?

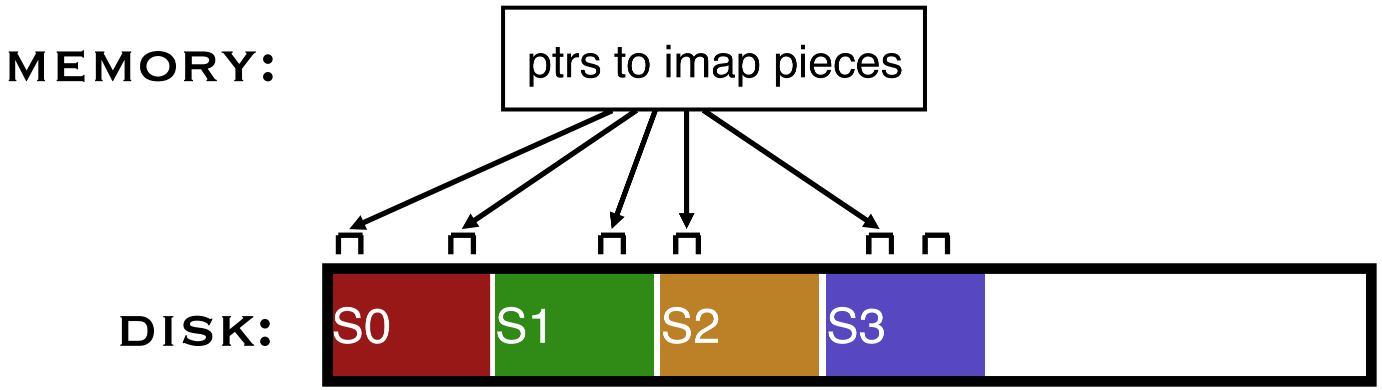
- Inodes are no longer at fixed offset
- Use imap structure to map:
  - inode number => most recent inode location on disk

Where to keep Imap?



- **Where can imap be stored? Dilemma:**
  1. imap too large to keep in memory
  2. don't want to perform random writes for imap
- **Solution: Write imap in segments**
  - Keep pointers to pieces of imap in memory

Solution: Imap in Segments



- **Solution:**
  - Write imap in segments
  - Keep pointers to pieces of imap in memory
  - Keep recent accesses to imap cached in memory

Disk Cleaning

- **When disk runs low on free space**
  - Run a disk cleaning process
  - Compacts live information to contiguous blocks of disk
- **Problem: long-lived data repeatedly copied over time**
  - Solution: partition disk in to segments
  - Group older files into same segment
    - Do not clean segments with old files
- **Try to run cleaner when disk is not being used**

Next Time…

- **Read Chapter 42**