File systems: case studies

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Outline

- BSD’s Fast File System
- Log-structured File System

A Fast File System for UNIX

Marshall K. McKusick, William N. Joy, Samuel J. Leffler and Robert S. Fabry
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Why do we care about fast file system

- We want better performance!!!
- We want new features!

Let's make file systems great again!

Problems in the “old” file system

- Lots of seeks when accessing a file
  - inodes are separated from data locations
  - data blocks belong to the same file can be spread out
- Low bandwidth utilization
  - only the very last is retrieving data
  - 1 out 11 in our previous example — less than 10% if files are small
- Limited file size
- Crash recovery
- Device oblivious

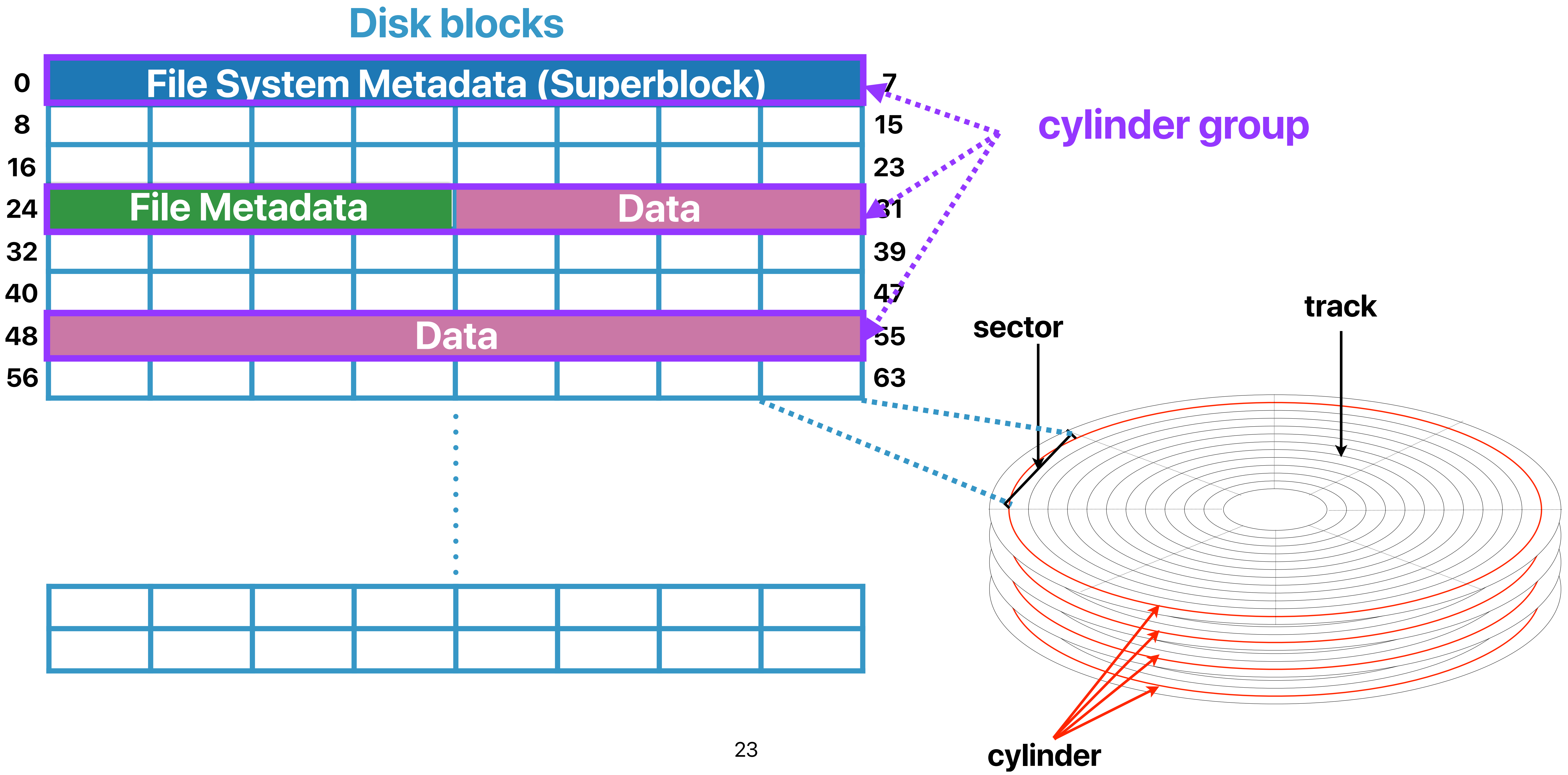
What does fast file system propose?

- Cylinder groups
- Larger block sizes
- Fragments
- Allocators
- New features
  - long file names
  - file locking
  - symbolic links
  - renaming
  - quotas

Cylinder groups

- Consists of one or more consecutive cylinders on a disk
- Each cylinder group contains the following
  - redundant copy of the superblock
    - what's the benefit?
    - why not a cylinder group for all superblocks?
  - inode space
  - bitmap of free blocks within the cylinder group
  - summary of block usage
  - data
- Improves average disk access time
  - Allocating blocks within the same cylinder group for the same file
  - Placing inode along with data within the same cylinder group

How FFS use disk blocks



Larger block sizes

- The block size of the old file system is aligned with the block (sector) size of the disk
  - Each file can only contain a fixed number of blocks
  - Cannot fully utilize the I/O interface bandwidth
- The new file system supports larger block sizes
  - Supports larger files
  - Each I/O request can carry more data to improve bandwidth
- However, larger block size leads to internal fragments

How larger block sizes improves bandwidth

- SATA II (300MB/s in theory), 7200 R.P.M., seek time around 8 ms. Assume the controller overhead is 0.2ms. What's the bandwidth of accessing 512B sectors and 4MB consecutive sectors?

Latency = seek time + rotational delay + transfer time + controller overhead

$$= 8\ ms + 4.17\ ms + 13.33\ ms + 0.2\ ms = 25.69\ ms$$

Bandwidth = volume_of_data over period_of_time

$$= \frac{4MB}{25.69ms} = 155.7\ MB/sec$$

Trading latencies with bandwidth

$$= 8\ ms + 4.17\ ms + 0.00167\ us + 0.2\ ms = 12.36\ ms$$

$$= \frac{0.5KB}{12.36ms} = 40.45KB/sec$$

Fragments

- Addressable units within a block
- Allocates fragments from a block with free fragments if the writing file content doesn’t fill up a block

Allocators

- Global allocators
  - Try to allocate inodes belong to same file together
  - Spread out directories across the disk to increase the successful rate of the previous
- Local allocators — allocate data blocks upon the request of the global allocator
  - Rotationally optimal block in the same cylinder
  - Allocate a block from the cylinder group if global allocator needs one
  - Search for blocks from other cylinder group if the current cylinder group is exhausted

Writes

- Larger overheads than the old file system as the new file system allocates blocks after write requests occur — Why not optimize for writes?
  - 10% of overall time
  - writes are a lot faster already
- Writing metadata is synchronous rather than asynchronous — What's the benefit of synchronous writes?
  - Consistency

What does fast file system propose?

- Cylinder groups — improve spread-out data locations
- Larger block sizes — improve bandwidth and file sizes
- Fragments — improve low space utilization due to large blocks
- Allocators — address device oblivious
- New features
  - long file names
  - file locking
  - symbolic links
  - renaming
  - quotas

The design and implementation of a log-structured file system

Mendel Rosenbaum and John K. Ousterhout
Univ. of California, Berkeley

Why LFS?

- Writes will dominate the traffic between main memory and disks — Unix FFS is designed under the assumption that only 10% of the traffic are writes
  - Who is wrong? **UFS is published in 1984**
  - As system memory grows, frequently read data can be cached efficiently
  - Every modern OS aggressively caches — use "free" in Linux to check
- Gaps between sequential access and random access
- Conventional file systems are not RAID aware

Why LFS?

- How many of the following problems is/are Log-structured file systems trying address?
  - ① The performance of small random writes ✓
  - ② The efficiency of large file accesses
  - ③ The space overhead of metadata in the file system
  - ④ Reduce the main memory space used by the file system

  A. 0
  B. 1
  C. 2
  D. 3
  E. 4

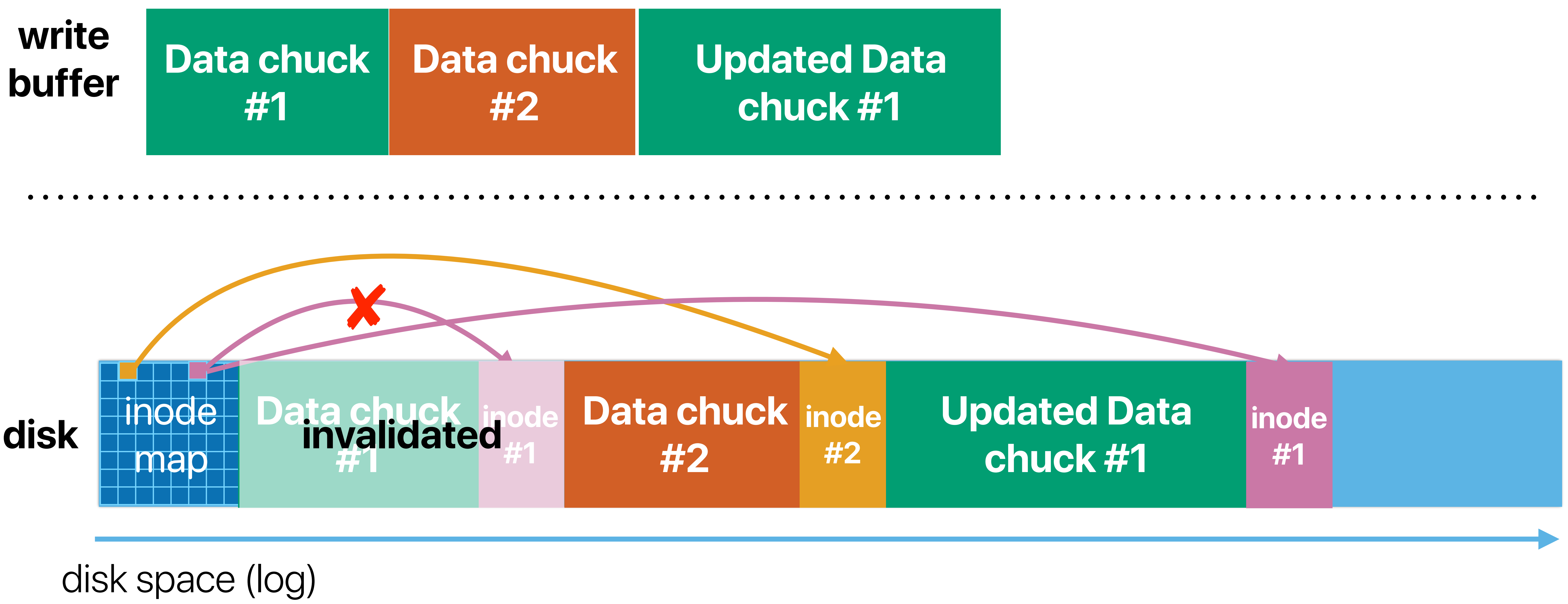
Problems with BSD FFS

- Data are spread out the whole disk
  - Can achieve sequential access within each file, but the distance between files can be far
  - An inode needs a standalone I/O in addition to file content
  - Creating files take at least five I/Os with seeks — can only use 5% bandwidth for data
    - 2 for file attributes
      - You have to check if the file exists or not
      - You have to update after creating the file
    - 1 for file data
    - 1 for directory data
    - 1 for directory attributes
- Writes to metadata are synchronous
  - Good for crash recovery, bad for performance

What does LFS propose?

- Buffering changes in the system main memory and commit those changes sequentially to the disk with fewest amount of write operations

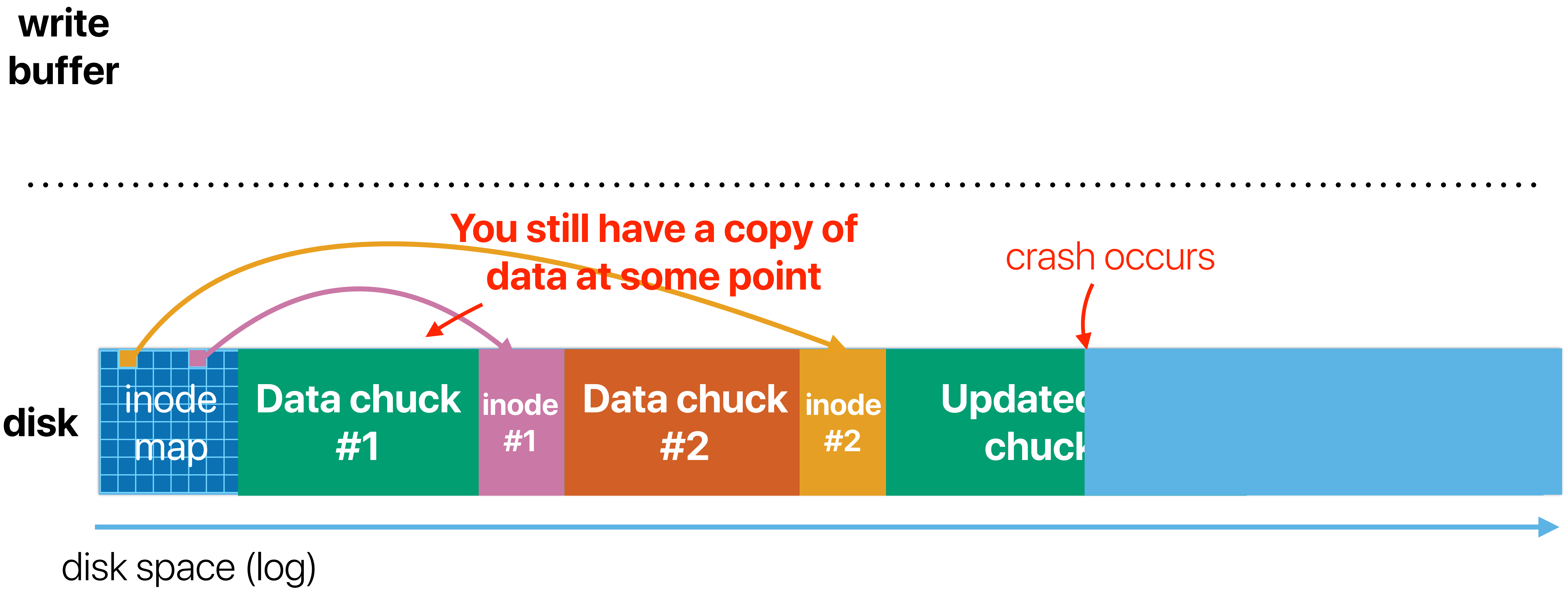
LFS in motion



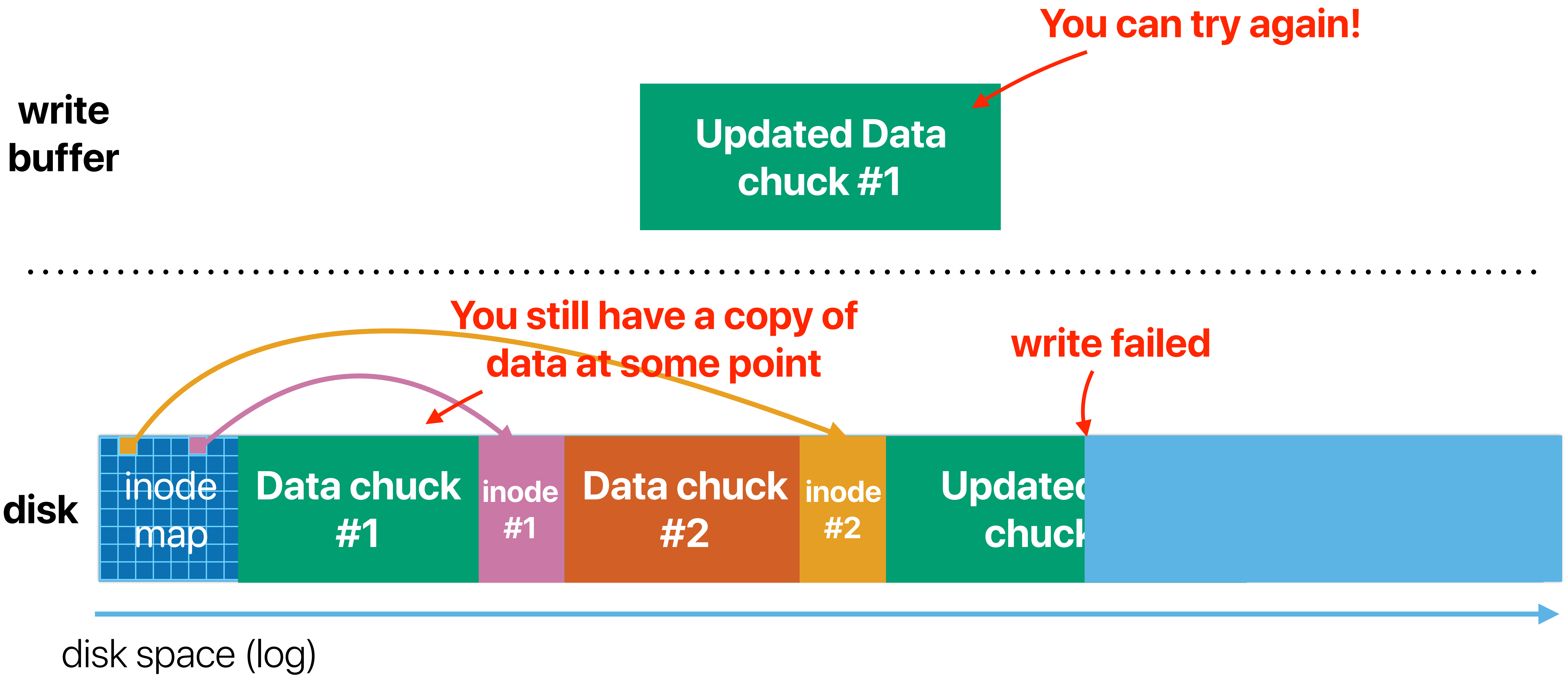
Crash recovery

- Checkpointing
  - Create a redundant copy of important file system metadata periodically
- Roll-forward
  - Scan through/replay the log after checkpointing

LFS v.s. crash


write
buffer
You still have a copy of
data at some point
crash occurs
disk
inode
map
Data chuck
#1
inode
#1
Data chuck
#2
inode
#2
Updated
chuck
disk space (log)

LFS v.s. write failed



Segment cleaning/Garbage collection

- Reclaim invalidated segments in the log once the latest updates are checkpointed
- Rearrange the data allocation to make continuous segments
- Must reserve enough space on the disk
  - Otherwise, every writes will trigger garbage collection
  - Sink the write performance

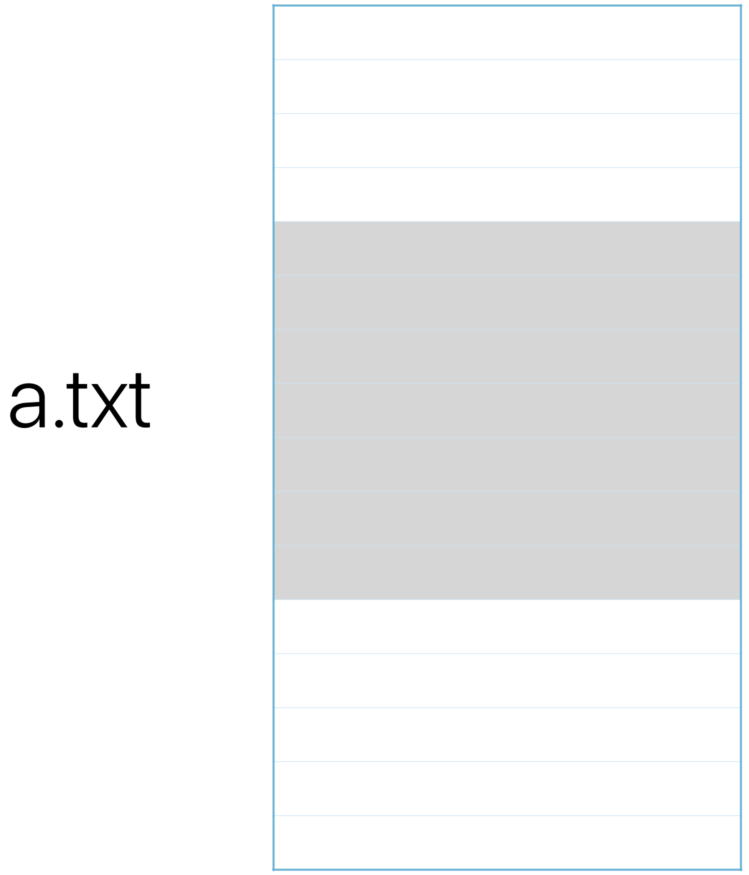
Modern file system design — Extent File Systems

Extent file systems — ext2, ext3, ext4

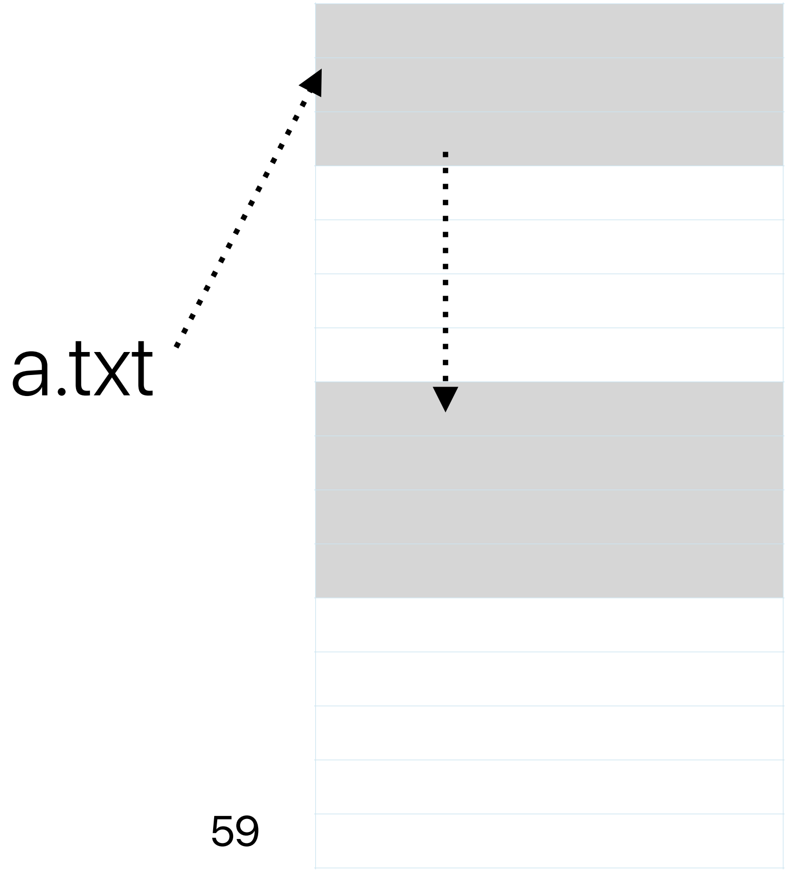
- Basically optimizations over FFS + Extent + Journaling (write-ahead logs)

How do we allocate space?

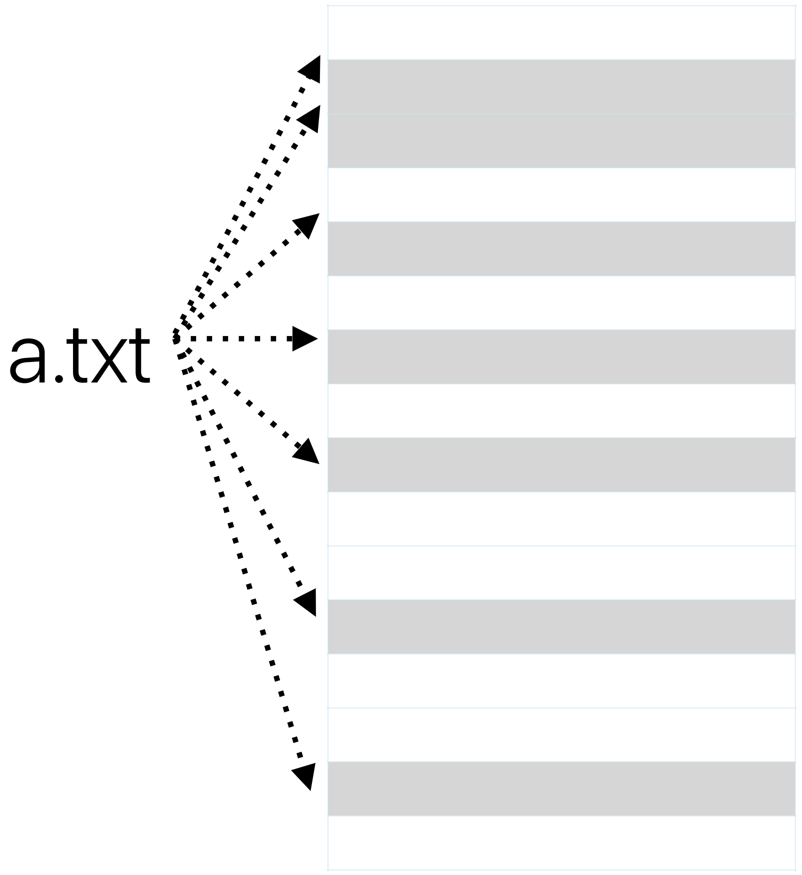
- Contiguous: the file resides in continuous addresses



- Extents: the file resides in several group of smaller continuous address



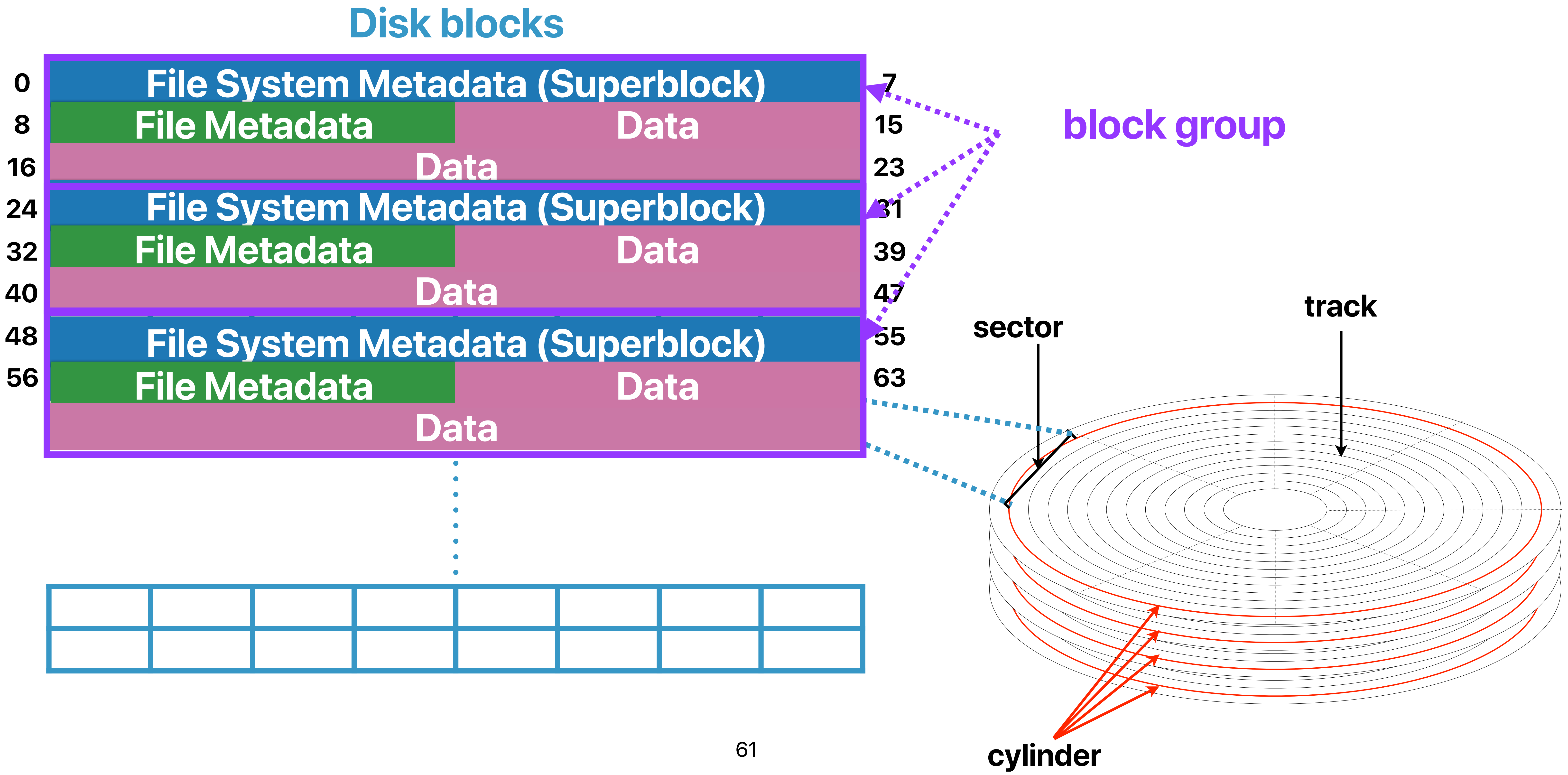
- Non-contiguous: the file can be anywhere



Using extents in inodes

- Contiguous blocks only need a pair <start, size> to represent
- Improve random seek performance
- Save inode sizes
- Encourage the file system to use contiguous space allocation

How ExtFS use disk blocks



Write-ahead log

- Basically, an idea borrowed from LFS to facilitate writes and crash recovery
- Write to log first, apply the change after the log transaction commits
  - Update the real data block after the log writes are done
  - Invalidate the log entry if the data is presented in the target location
  - Replay the log when crash occurs