CSC 369

Week 10:

Disk I/O and File System Optimization

University of Toronto, Department of Computer Science

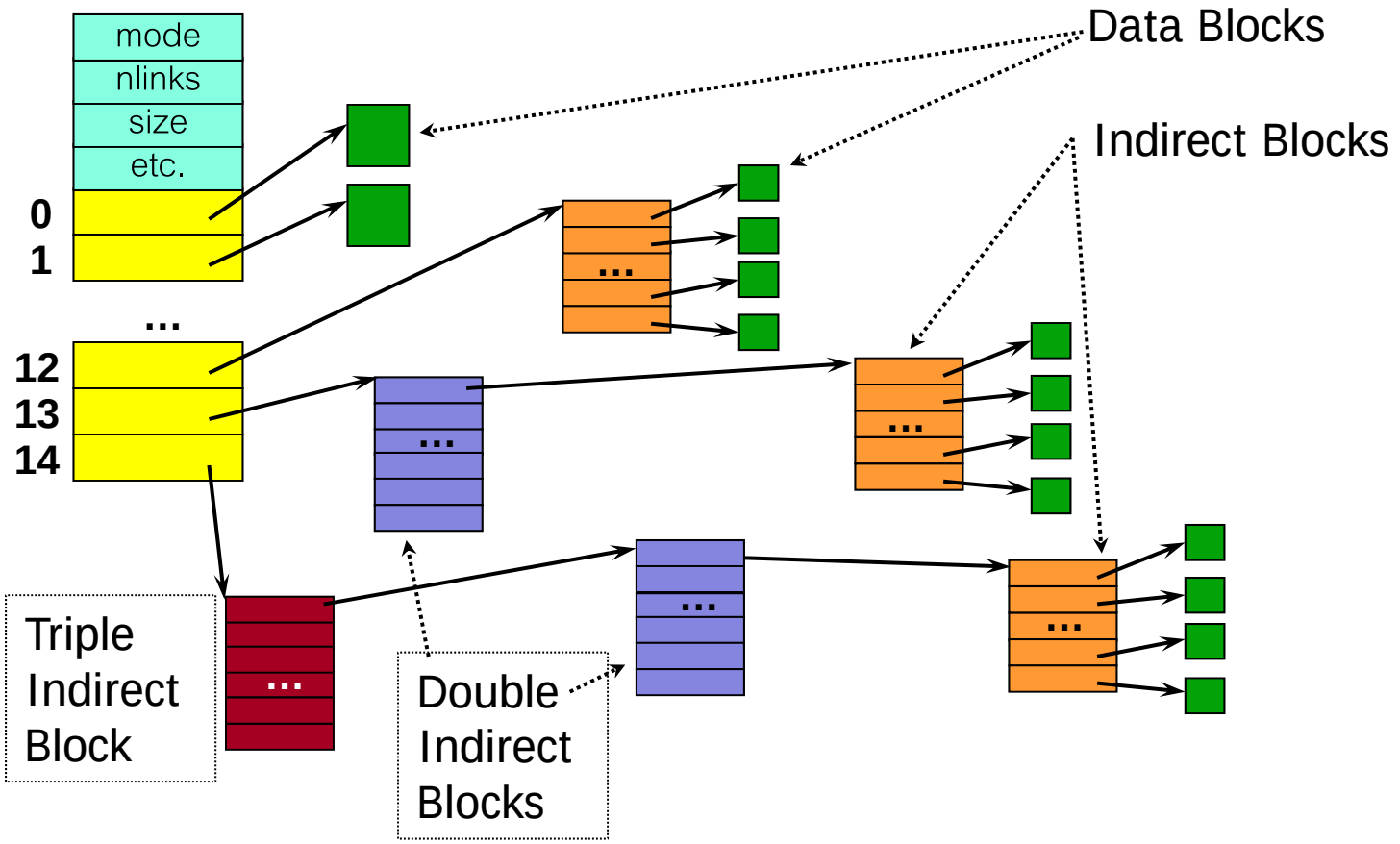
Overview

- Last time:
  - File systems – Interface, structure, basic implementation
- This week:
  - Review FS basics in more detail
  - UNIX inode structure
  - File system optimizations
  - Magnetic disks as secondary storage
  - Disk scheduling

Review of File Systems

- Many file system implementations, literally from AFS to ZFS
  - Check out https://en.wikipedia.org/wiki/List_of_file_systems
- Most well-known:
  - Windows: FAT32, NTFS
  - MAC OS X: HFS+
  - BSD, Solaris: UFS, ZFS
  - Linux: ext2 (see A4 too!), ext3, ext4, ReiserFS, XFS, JFS, btrfs, etc.
- We'll have a look at a very simple file system (VSFS)
  - See readings as well!

Remember: inode-based FS organization



The main idea

- We need to create a file system for an unformatted disk
- We need to create some structure in it, so that things (data) will be easy to find and organize
- Key questions
  - Where do we store file data and metadata structures (inodes)?
  - How do we keep track of data allocations?
  - How do we locate file data and metadata?
  - What are the limitations (max file size, etc.)?

Bad programmers worry about the code.
Good programmers worry about data structures and their relationships.

-- Linus Torvalds

Implementation of a Very Simple File System (VSFS)

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An unformatted raw disk

Total size = 256KB

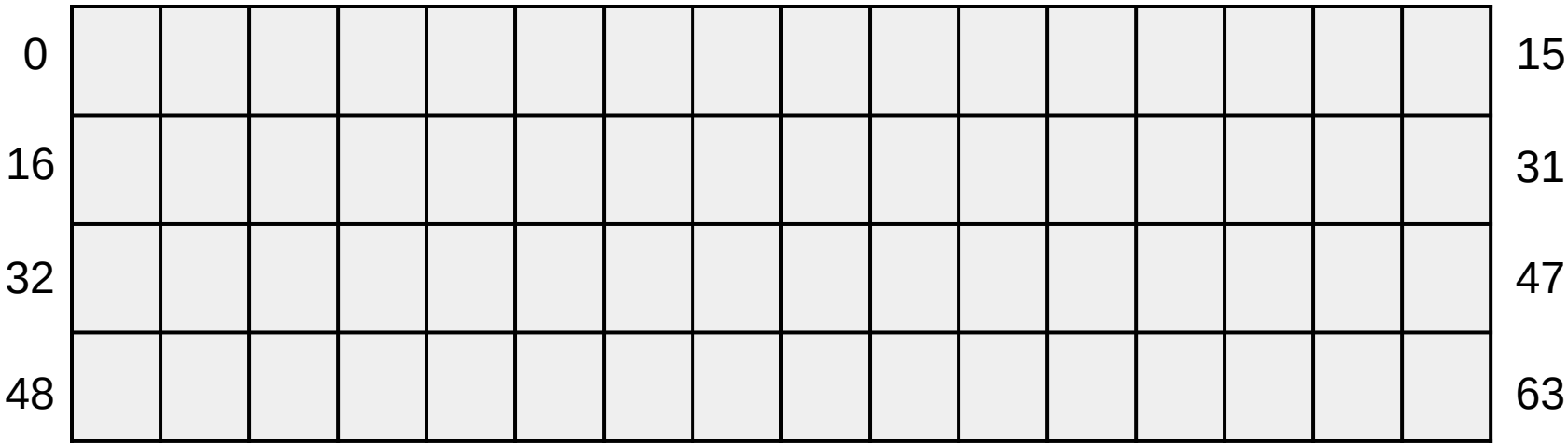
Overall Organization

The whole disk is divided into fixed-sized blocks.

Block size: 4KB

Number of blocks: 64

Total size: 256KB



Data Region

Most of the disk should be used to actually store user data, while leaving a little space for storing other things like **metadata**.

In VSFS, we reserve the **last 56 blocks** as data region.

0									D	D	D	D	D	D	D	D	15
16	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	31
32	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	47
48	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	63

Metadata: inode table

FS needs to track information about each file.

In VSFS, we keep the info of each file in a struct called inode. And we use 5 blocks for storing all the inodes.

Size	Name	What is this inode field for?
2	mode	can this file be read/written/executed?
2	uid	who owns this file?
4	size	how many bytes are in this file?
4	time	what time was this file last accessed?
4	ctime	what time was this file created?
4	mtime	what time was this file last modified?
4	dtime	what time was this inode deleted?
2	gid	which group does this file belong to?
2	links_count	how many hard links are there to this file?
4	blocks	how many blocks have been allocated to this file?
4	flags	how should ext2 use this inode?
4	osd1	an OS-dependent field
60	block	a set of disk pointers (15 total)
4	generation	file version (used by NFS)
4	file_acl	a new permissions model beyond mode bits
4	dir_acl	called access control lists
4	faddr	an unsupported field
12	i_osd2	another OS-dependent field

ext2 inode with size of 128B

0				I	I	I	I	I	D	D	D	D	D	D	D	D	15
16	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	31
32	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	47
48	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	63

How many files can this VSFS hold at most?

Maximum number of inodes it can hold: 5 * 4KB / 128B = 160 => can store at most 160 files.

Allocation Structures

- Keep track of which blocks are being used and which ones are free
- We use a data structure (a **bitmap**) for this purpose
  - Each bit indicates if one block is free (0) or in-use (1)
- A bitmap for the **data region** and a bitmap for the **inode region**
  - Reserve one block for each bitmap.

0		IB	DB	I	I	I	I	I	D	D	D	D	D	D	D	D	15
16	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	31
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How many blocks can a 4KB data bitmap keep track of?
4KB = 32K bits, can keep track of 32K blocks, so yeah it's overkill in this VSFS.

Superblock

- Superblock contains information about this particular file system:
  - what type of file system it is ("VSFS" indicated by a magic number)
  - how many inodes and data blocks are there (160 and 56)
  - where the inode table begins (block 3), etc.

0	S	IB	DB	I	I	I	I	I	D	D	D	D	D	D	D	D	15
16	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	31
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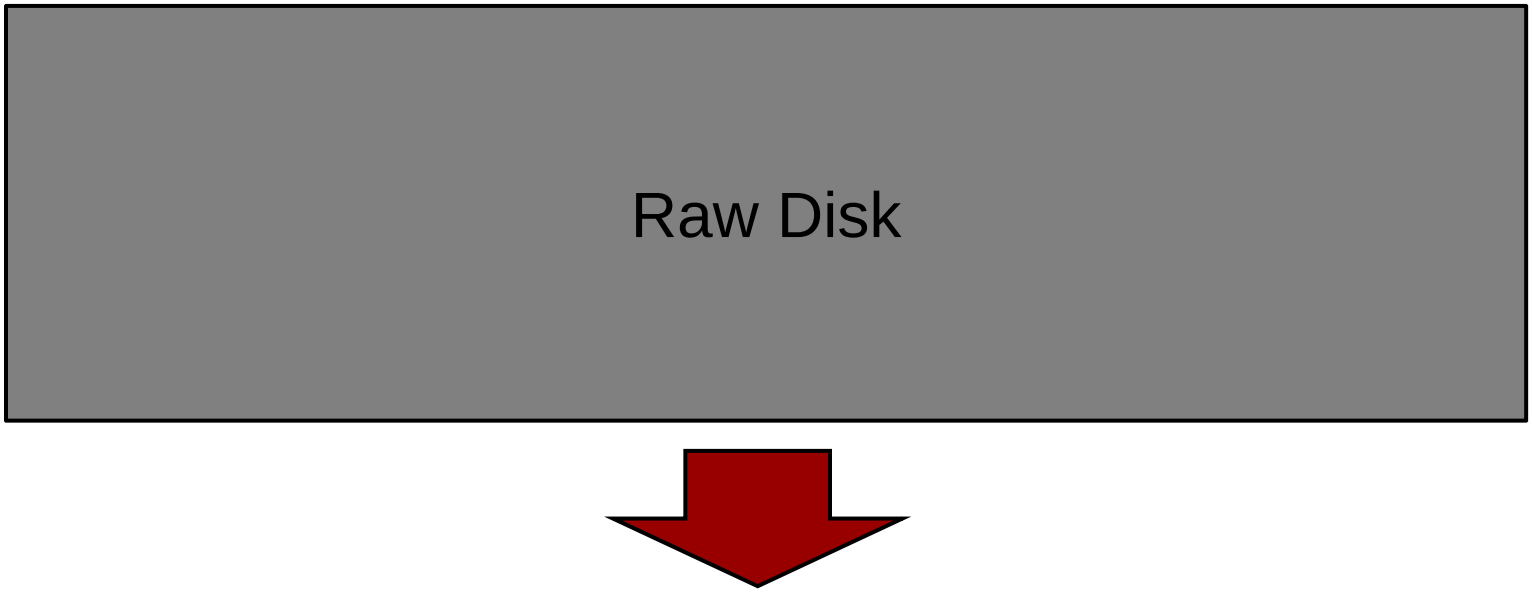
When mounting a file system, the OS first reads the superblock, identifies its type and other parameters, then attaches the volume to the file system tree with proper settings.

Formatting disk into VSFS, done!



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16	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	31
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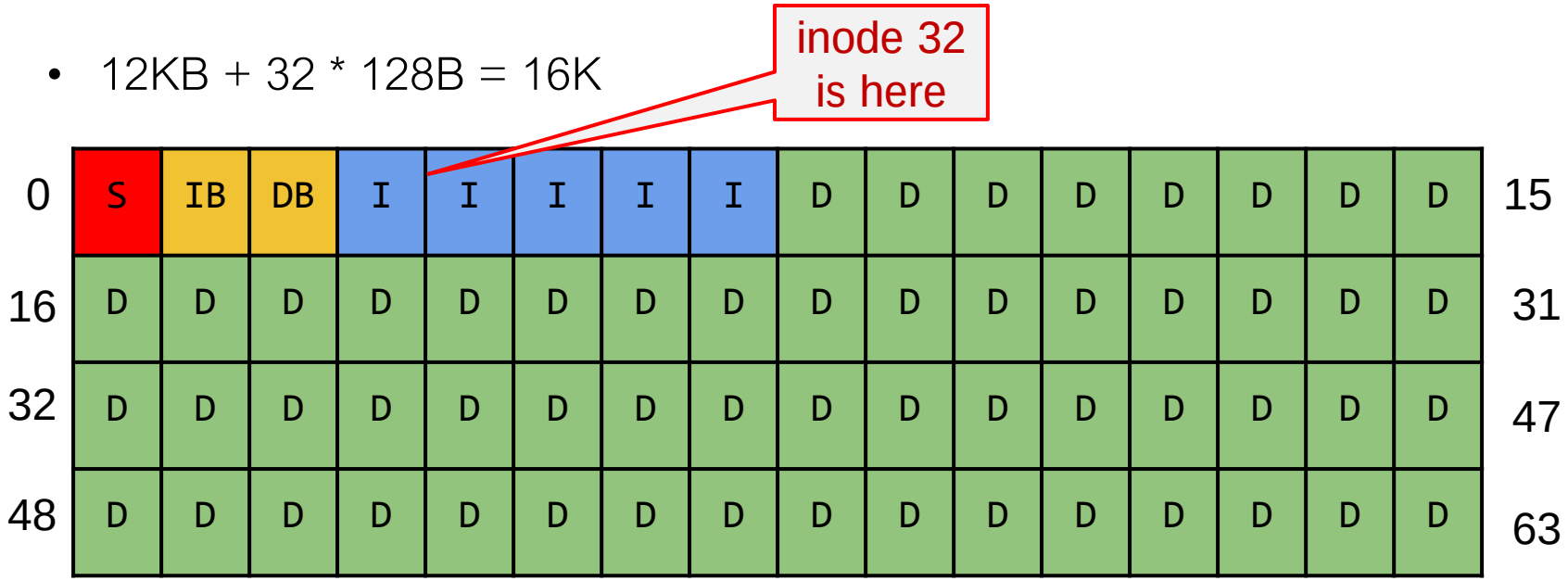
Example: Read a file with inode number 32

- From the superblock, we know
  - inode table begins at Block 3, i.e., 12KB
  - inode size is 128B
- Calculate the address of inode 32
  - 12KB + 32 * 128B = 16K



So we have the inode, but which blocks have the **data**?

From inode to data

- Say the inode contains an array of 15 **direct pointers** that point to 15 data blocks that belong to the file.
- Maximum file size supported:
  - 15 * 4KB = 60KB
- If we need a file larger than 60KB, we need to do something more sophisticated.

Size	Name	What is this inode field for?
2	mode	can this file be read/written/executed?
2	uid	who owns this file?
4	size	how many bytes are in this file?
4	time	what time was this file last accessed?
4	ctime	what time was this file created?
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48	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D

15 31 47 63

Multi-Level Index with Indirect Pointers

- Direct pointers to disk blocks do not support large files
- Idea: **indirect pointer**
  - Instead of pointing to a block of **user data,** it points to a block that contains **more pointers**
  - From the 15 pointers we have in an inode, use the first 14 as direct pointers and 15th as an indirect pointer
- **How big a file can we support now?**
  - 14 direct pointers in total: 14 data blocks
  - Indirect pointer points to a block (4KB) which can hold 1K pointers => 1K data blocks in addition
  - Total size supported: 4K * (14 + 1K) = **4152KB**

What if I want even BIGGER?

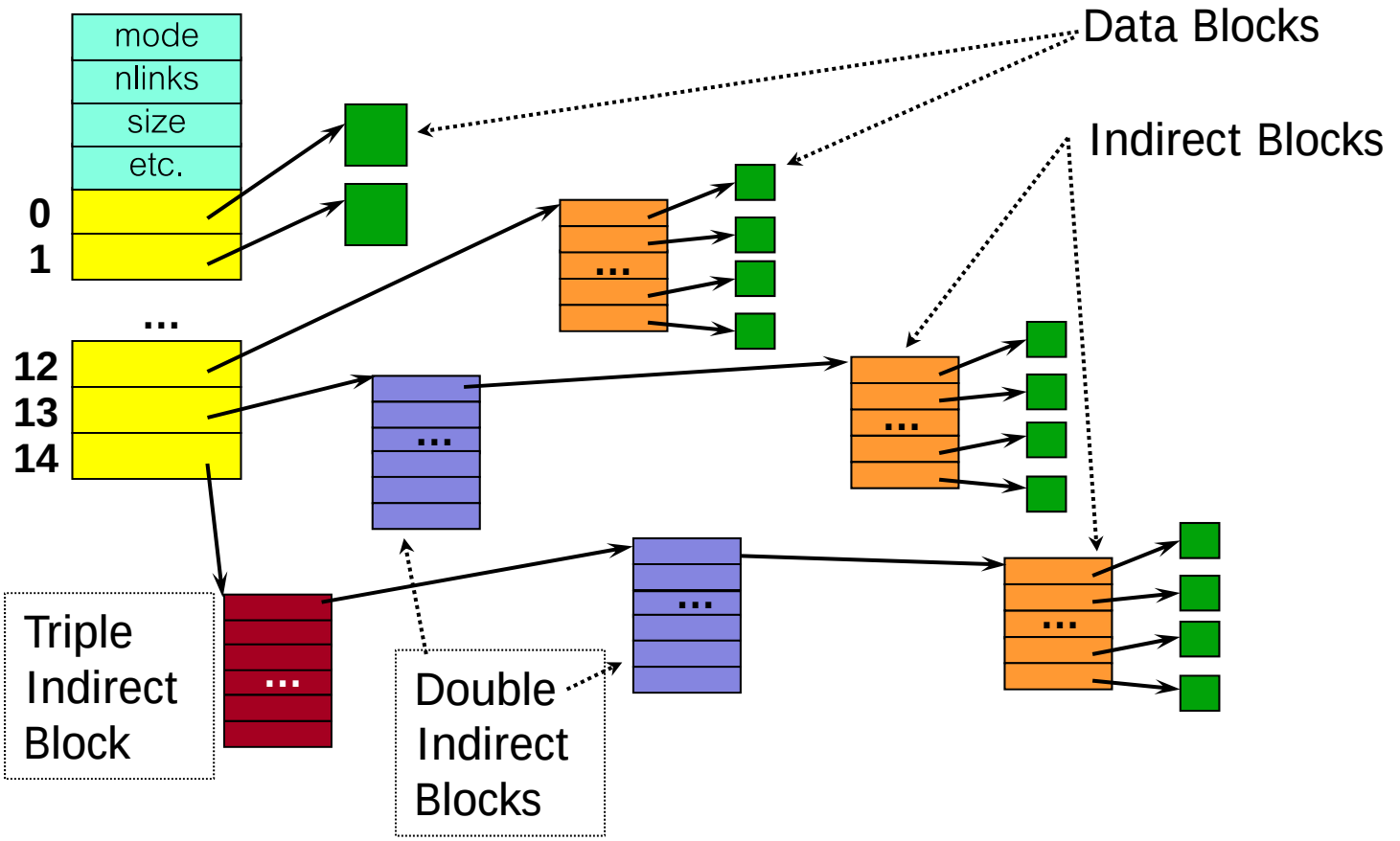
Double Indirect Pointer!

- A **double indirect pointer** points to **a block full of indirect pointers** which point to **blocks of direct pointers**.
  - E.g., for the 15 pointers, we use the first 13 as direct pointers, the 14th as an indirect pointer, and the 15th as a double indirect pointer.

- **How big a file do we support now?**
  - From direct pointers: 13 data blocks
  - From indirect pointers: 1024 data blocks
  - From double indirect pointers: 1024 * 1024 = 1M data blocks
  - Total size = 4K * (13 + 1024 + 1024*1024) ≈ **4.004GB**

Still not big enough? Use a Triple Indirect Pointer

A tree-view of multi-level indirect pointers



A tree-view of multi-level indirect pointers

- You might wonder: this tree is super **imbalanced**.
- Frequently access big files => the blocks with the double and/or triple indirect pointers are going to be accessed like **crazy** (because most of the data blocks are in their subtrees).

- True, but it's fine: in practice, **most files are small.**
- For more practice-inspired decisions, read "*A Five-Year Study of File System Metadata*" (see course web page)

Another approach: extent-based

- An **extent** == a disk pointer plus a length (in # of blocks), i.e., it allocates a few blocks in a row.
- Instead of requiring a pointer to every block of a file, we just need a pointer to every several blocks (every extent).
- *Disadvantage:* Less flexible than the pointer-based approach
- *Advantages:* Uses smaller amount of metadata per file, and file allocation is more compact.
- Adopted by ext4, HFS+, NTFS, XFS.

Yet another approach: Linked-Based

- Instead of pointers to all blocks, the inode just has one pointer to the first data block of the file, then the first block points to the second block, etc.
- Works poorly if we want to access the last block of a big file.
- Use an in-memory **File Allocation Table**, indexed by address of data block
  - Faster in finding a block.
- FAT file system, used by Windows before NTFS.
- Focus on inode-based FSs in next lectures...

Summary

- Inodes
  - Data structure representing a FS object (file, dir, etc.)
  - Attributes, disk block locations
  - No file name, just metadata!
- Directory
  - List of (name, inode) mappings
  - Each directory entry: a file, other directory, link, itself (.), parent dir (..), etc.

Inodes and directories: Examples

- Inodes
  - Data structure representing a FS object (file, dir, etc.)
  - Attributes, disk block locations
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- Directory
  - List of (name, inode) mappings
  - Each directory entry: a file, other directory, link, itself (.), parent dir (..), etc.
- Use `stat` or `ls -if` to check out information!
- On your machine, info about your FS:
  - `sudo dumpe2fs –h /dev/sda1`
  - `df –Th`

Links: Examples

- Hard links
  - Multiple file names (and directory entries) mapped to the same inode
  - Reference count – only remove file when it reaches 0
- Soft (Symbolic) links
  - “Pointer” to a given file
  - Contains the path

The content of a data block

- If it belongs to a regular file
  - Data of the file
- If it belongs to a directory
  - List of directory entries: (name, inode number) pairs, which are the entries under the directory
- If it belongs to a symbolic link
  - The path of the file that it links to

Unix Inodes and Path Search

- Unix Inodes are not directories
- They describe where on the disk the blocks for a file are placed
  - Directories are files, so inodes also describe where the blocks for directories are placed on the disk
- Directory entries map file names to inodes
  - To open "/somefile", use Master Block to read the inode for "/"
  - inode allows us to find data block for directory "/"
  - Read data block for "/", look for entry for "somefile"
  - This entry identifies the inode for "somefile"
  - Read the inode for "somefile" into memory
  - The inode says where first data block is on disk
  - Read that block into memory to access the data in the file

Next up

☞ Performance optimizations …

Caching

- File operations (open() /read() / write()) incur a good amount of disk I/Os
- Then how can the file system perform reasonably well?
  - Caching!

File Buffer Cache

- Key observation: Applications exhibit significant locality for reading and writing files. How? (recall VM)
- Idea: Cache file blocks in memory to capture locality
  - This is called the file buffer cache
  - Cache is system wide, used and shared by all processes
  - Reading from the cache makes a disk perform like memory
  - Significant reuse: spatial and temporal locality
  - Even a 4 MB cache can be very effective
- What do we want to cache?
  - Inodes, directory entries, disk blocks for “hot” files, even whole files if small.

Caching and Buffering

- So, we use memory to cache important blocks
- Static partitioning: at boot time, allocate a fixed-size cache in memory (typically 10% of total memory) -- early file systems
- Dynamic partitioning: integrate virtual memory pages and file system pages into a unified page cache, so pages of memory can be flexibly allocated for either virtual memory or file system, used by modern systems
- *Replacement policy:* typically use LRU
- Tradeoff between static vs dynamic partitioning
  - Applicable to any resource allocation kind of problem!

Caching Writes

- Caching works really well for reads!
- For writes, not as much!
  - Writes still have to go to disk anyway to become persistent.
  - Once a block is modified in memory, the write back to disk may not be immediate (synchronous).

Caching Writes

- Use a buffer to buffer writes. Buffering a batch of disk writes is helpful because:
  - Combine multiple writes into one write
    - e.g., updating multiple bits of the inode bitmap
  - Can improve performance by scheduling the buffered writes (lazy updates)
    - e.g., can schedule buffered writes in such a way that they happen sequentially on disk.
  - Can avoid some writes
    - e.g., one write changes a bit from 0 to 1, then another write changes it from 1 to 0, if buffered than no need to write anything to disk

Tradeoff: speed vs durability

- Caching and buffering improves the speed of file system reads and writes
- However, it sacrifices the durability of data.
  - Crash occurs => buffered writes not written to disk yet, are lost
  - Better durability => sync to disk more frequently => worse speed
- Should I favour speed or durability?
  - It depends
  - On what? It depends on the application, e.g.,
    - web browser cache
    - bank database

Approaches?

- Several ways to address these concerns
  - Delayed writes only for a specific amount of time
    - How long do we hold dirty data in memory?
  - Asynchronous writes ("write-behind")
    - Maintain a queue of uncommitted blocks
    - Periodically flush the queue to disk
    - Unreliable
  - Battery backed-up RAM (NVRAM)
    - As with write-behind, but maintain queue in NVRAM
    - Expensive
  - Log-structured file system
    - Always write contiguously at end of previous write

Read Ahead

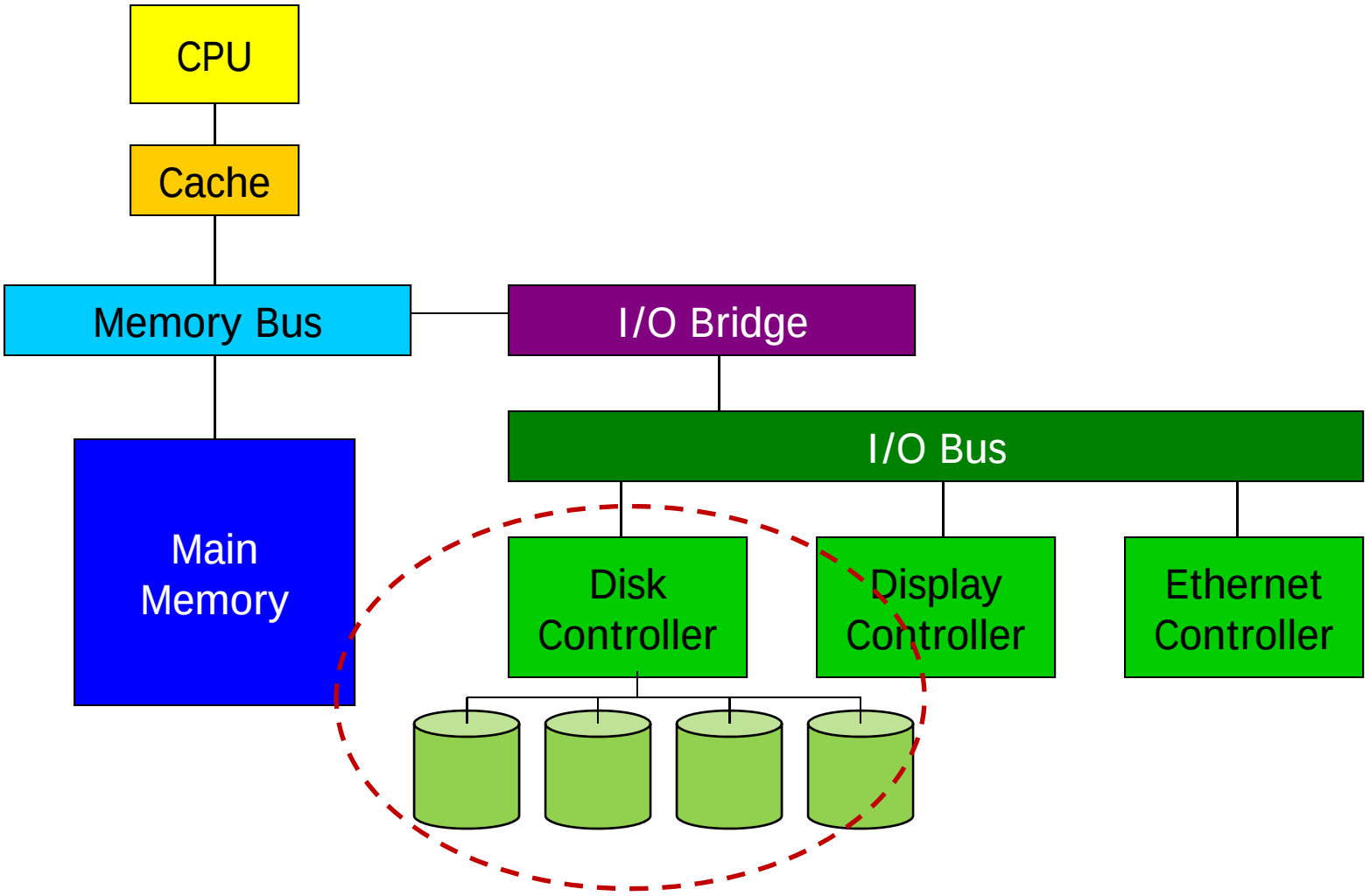
- Many file systems implement "read ahead"
  - FS predicts that the process will request next block
  - FS goes ahead and requests it from the disk
  - This can happen while the process is computing on previous block
    - Overlap I/O with execution
  - When the process requests block, it will be in cache
  - Compliments the on-disk cache, which also is doing read ahead
- For sequentially accessed files, can be a big win
  - Unless blocks for the file are scattered across the disk
  - File systems try to prevent that, though (during allocation)

Next up

- We looked at performance with caching, buffering, read-ahead
- What about the actual disk's physical characteristics?

☞ A closer look at secondary storage, where files live…

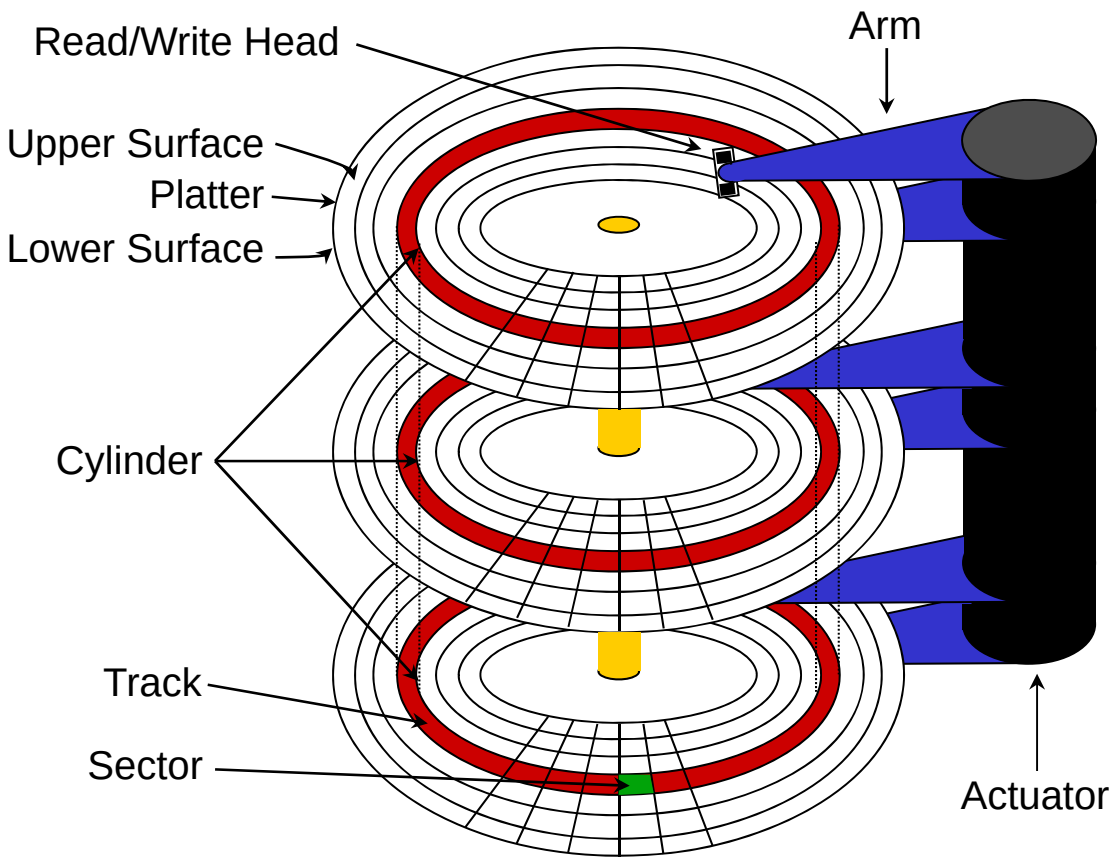
I/O Diagram


CPU
Cache
Memory Bus
I/O Bridge
I/O Bus
Main Memory
Disk Controller
Display Controller
Ethernet Controller

Secondary Storage Devices

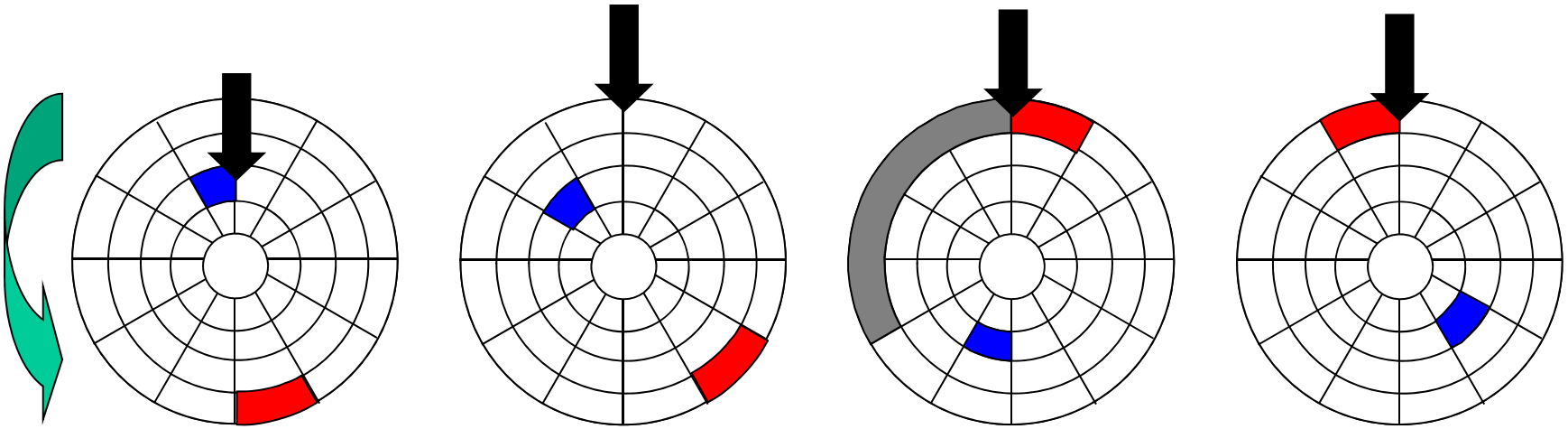
- Drums
  - Ancient history
- Magnetic disks
  - Fixed (hard) disks
  - Removable (floppy) disks
- Optical disks
  - Write-once, read-many (CD-R, DVD-R)
  - Write-many, read-many (CD-RW)
- We're going to focus on the use of fixed (hard) magnetic disks for implementing secondary storage

Disk Components



Disk Performance

- Disk request performance depends on a number of steps
  - Seek – moving the disk arm to the correct cylinder
    - Depends on how fast disk arm can move
    - Typical times: 1-15ms, depending on distance (avg 5-6 ms)
    - Improving very slowly (7-10% per year)
  - Rotation – waiting for the sector to rotate under the head
    - Depends on rotation rate of disk (7200 RPM SATA, 15K RPM SCSI)
    - Average latency of ½ rotation (~4 ms for 7200 RPM disk)
    - Has not changed in recent years
  - Transfer – transferring data from surface into disk controller electronics, sending it back to the host
    - Depends on density (increasing quickly)
    - ~100 MB/s, average sector transfer time of ~5us
    - improving rapidly (~40% per year)



Traditional service time components

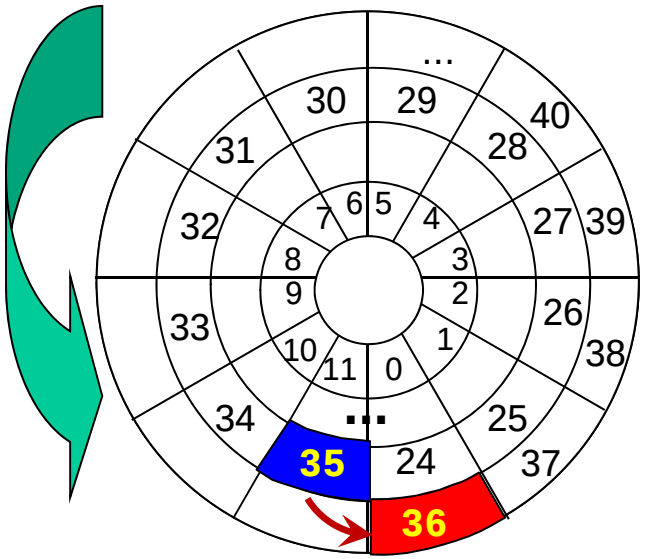
After BLUE read | **Seek** for RED | **Rotational latency** | After RED read

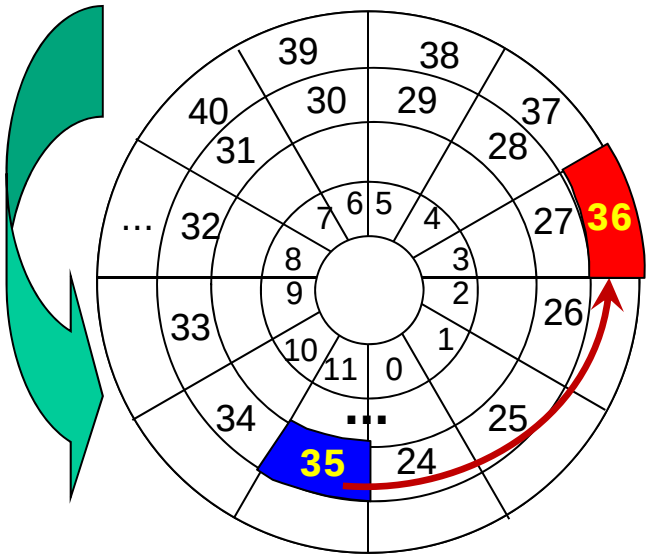
- When the OS uses the disk, it tries to minimize the cost of all of these steps
  - Particularly seeks and rotation

Some hardware optimizations

- Track skew
- Zones
- Cache

Track skew

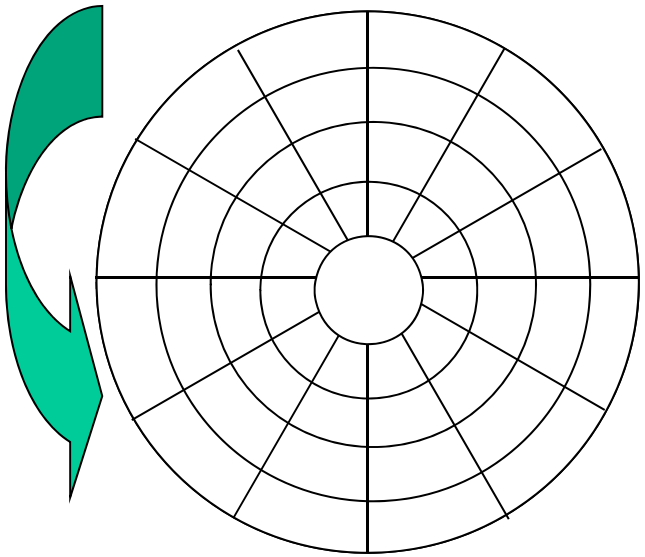


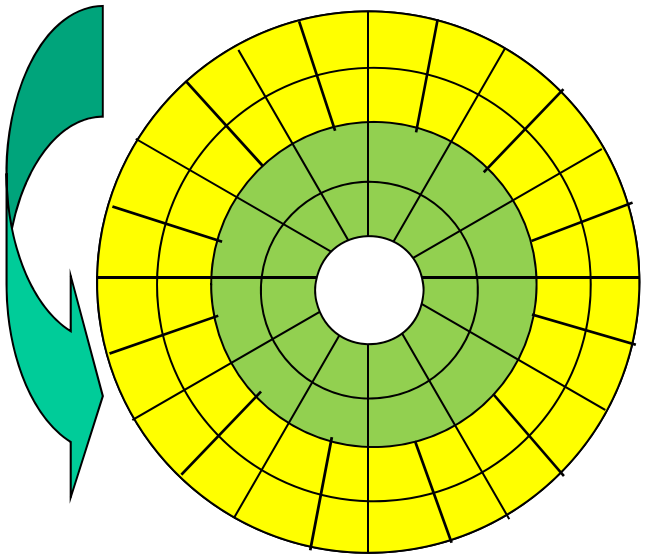


If the arm moves to outer track too slowly, may miss sector 36 and have to wait for a whole rotation.

Instead, skew the track locations, so that we have enough time to position.

Zones





Each sector is 512 bytes
Notice anything though?

Outer tracks are larger by geometry, so they should hold more sectors.

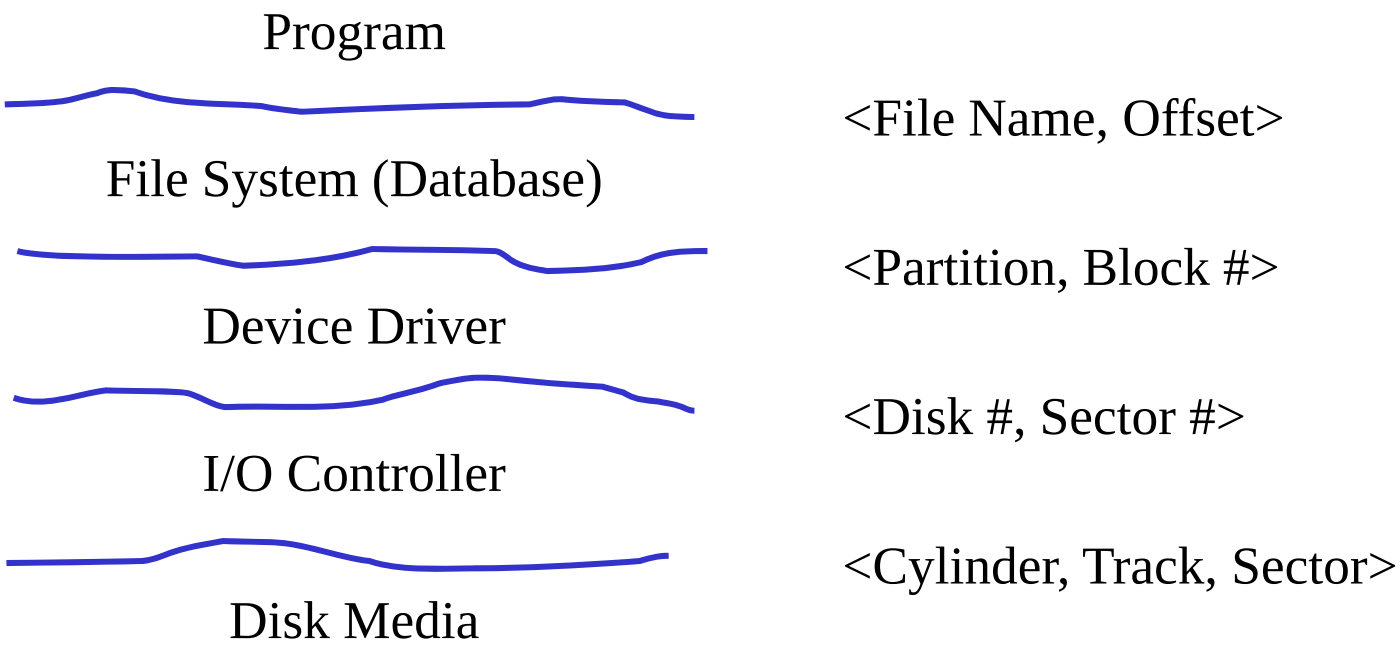
Cache, aka Track Buffer

- A small memory chip, part of the hard drive
  - Usually 8-16MB
- Different from cache that OS has
  - Unlike the OS cache, it is aware of the disk geometry
  - When reading a sector, may cache the whole track to speed up future reads on the same track

Disks and the OS

- Disks are messy physical devices:
  - Errors, bad blocks, missed seeks, etc.
- The job of the OS is to hide this mess from higher level software
  - Low-level device control (initiate a disk read, etc.)
  - Higher-level abstractions (files, databases, etc.)
- The OS may provide different levels of disk access to different clients
  - Physical disk (surface, cylinder, sector)
  - Logical disk (disk block #)
  - Logical file (file block, record, or byte #)

Software Interface Layers

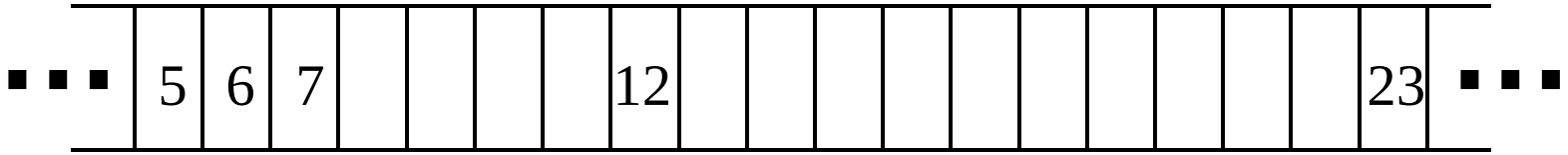


- Each layer abstracts details below it for layers above it

Disk Interaction

- Specifying disk requests requires a lot of info:
  - Cylinder #, surface #, track #, sector #, transfer size…
- Older disks required the OS to specify all of this
  - The OS needed to know all disk parameters
- Modern disks are more complicated
  - Not all sectors are the same size, sectors are remapped, etc.
- Current disks provide a higher-level interface (SCSI)
  - The disk exports its data as a logical array of blocks [0…N]
    - Disk maps logical blocks to cylinder/surface/track/sector
  - Only need to specify the logical block # to read/write
  - But now the disk parameters are hidden from the OS

The common storage device interface



OS's view of storage device

Storage exposed as linear array of blocks

- Common block size: 512 bytes
- Number of blocks: device capacity / block size

Back to File Systems…

- Key idea: File systems need to be aware of disk characteristics for performance
  - Allocation algorithms to enhance performance
  - Request scheduling to reduce seek time

Enhancing achieved disk performance

- High-level disk characteristics yield two goals:
  - Closeness
    - reduce seek times by putting related things close to each other
    - generally, benefits can be in the factor of 2 range
  - Amortization
    - amortize each positioning delay by grabbing lots of useful data
    - generally, benefits can reach into the factor of 10 range

Allocation strategies

- Disks perform best if seeks are reduced and large transfers are used
  - Scheduling requests is one way to achieve this
  - Allocating related data "close together" on the disk is even more important

FFS: a disk-aware file system

Original Unix File System

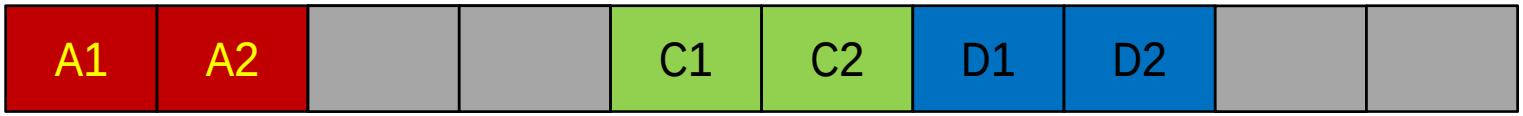
- Recall FS sees storage as linear array of blocks
  - Each block has a *logical block number (LBN)*

- Simple, straightforward implementation
  - Easy to implement and understand
  - But very poor utilization of disk bandwidth. Why?

Data and Inode Placement – problem #1

- On a new FS, blocks are allocated sequentially, close to each other.

- As the FS gets older, files are being deleted and create random gaps



- In aging file systems, data blocks end up allocated far from each other:

- Data blocks for new files end up scattered across the disk!
- Fragmentation of an aging file system causes more seeking!

Data and Inode Placement – problem #2

- Inodes allocated far from blocks
  - All inodes at beginning of disk, far from data
- Recall that when we traverse a file path, at each level we inspect the inode first, then access the data block.
  - Traversing file name paths, manipulating files, directories requires going back and forth from inodes to data blocks
- => Again, lots of seeks!

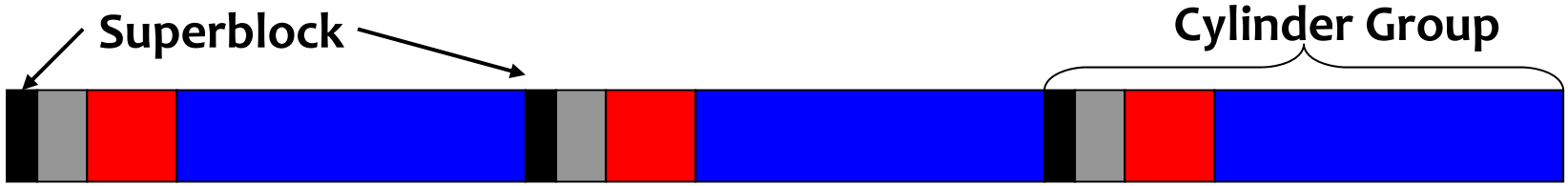
FFS

- BSD Unix folks did a redesign (early-mid 80s?) that they called the Fast File System (FFS)
  - Improved disk utilization, decreased response time
  - McKusick, Joy, Leffler, and Fabry, ACM TOCS, Aug. 1984
- A major breakthrough in the history of File Systems
- All modern FSs draw from the lessons learned from FFS

- Good example of being device-aware for performance!

Cylinder Groups

- BSD FFS addressed placement problems using the notion of a cylinder group (aka *allocation groups* in lots of modern FS's)
  - Disk partitioned into groups of cylinders
  - Data blocks in same file allocated in same cylinder group
  - Files in same directory allocated in same cylinder group
  - Inodes for files are allocated in same cylinder group as file data blocks



Cylinder group organization

Cylinder Groups (continued)

- Allocation in cylinder groups provides *closeness*
  - Reduces number of long seeks
- Free space requirement
  - To be able to allocate according to cylinder groups, the disk must have free space scattered across cylinders
  - 10% of the disk is reserved just for keeping the disk partially free all the time
  - When allocating large files, break it into large chunks and allocate from different cylinder groups, so it does not fill up one cylinder group
  - If preferred cylinder group is full, allocate from a “nearby” group

More FFS solutions

- Small blocks (1K) in orig. Unix FS caused 2 problems:
  - Low bandwidth utilization
  - Small max file size (function of block size)
- Fix using a larger block (4K)
  - Very large files, only need two levels of indirection for 2^32
  - New Problem: internal fragmentation
  - Fix: Introduce “fragments” (1K pieces of a block)
- Problem: Media failures
  - Replicate master block (superblock)
- Problem: Device oblivious
  - Parameterize according to device characteristics

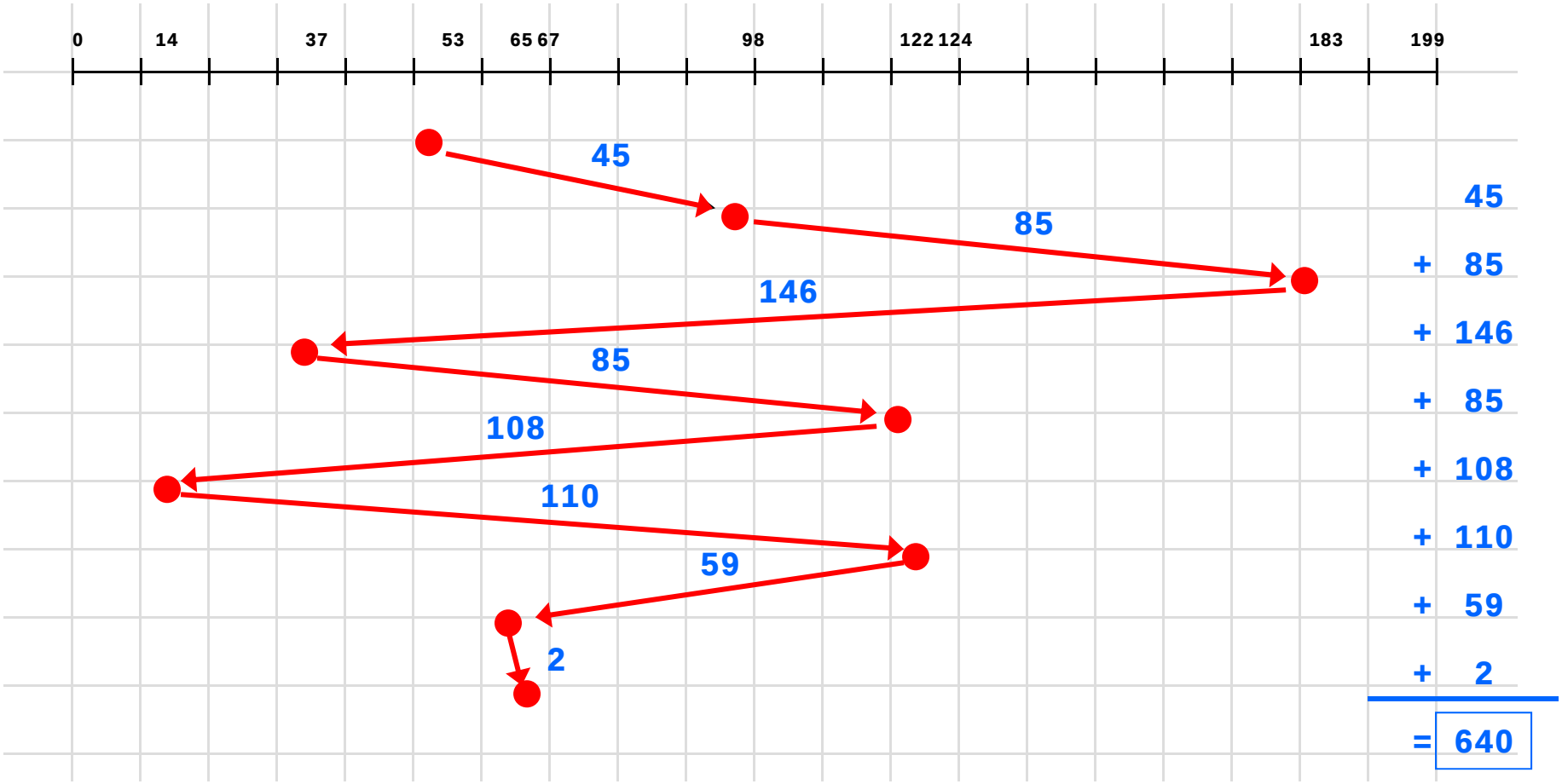
Disk Scheduling Algorithms

- Because seeks are so expensive (milliseconds!), OS tries to schedule disk requests that are queued waiting for the disk
- Goal: Minimize seeks!
- Policies:
  - FCFS (do nothing)
    - Reasonable when load is low
    - Long waiting times for long request queues
  - SSTF (shortest seek time first)
    - Minimize arm movement (seek time), maximize request rate
    - Favors middle blocks
  - SCAN (elevator)
    - Service requests in one direction until done, then reverse
  - C-SCAN
    - Like SCAN, but only go in one direction (typewriter)

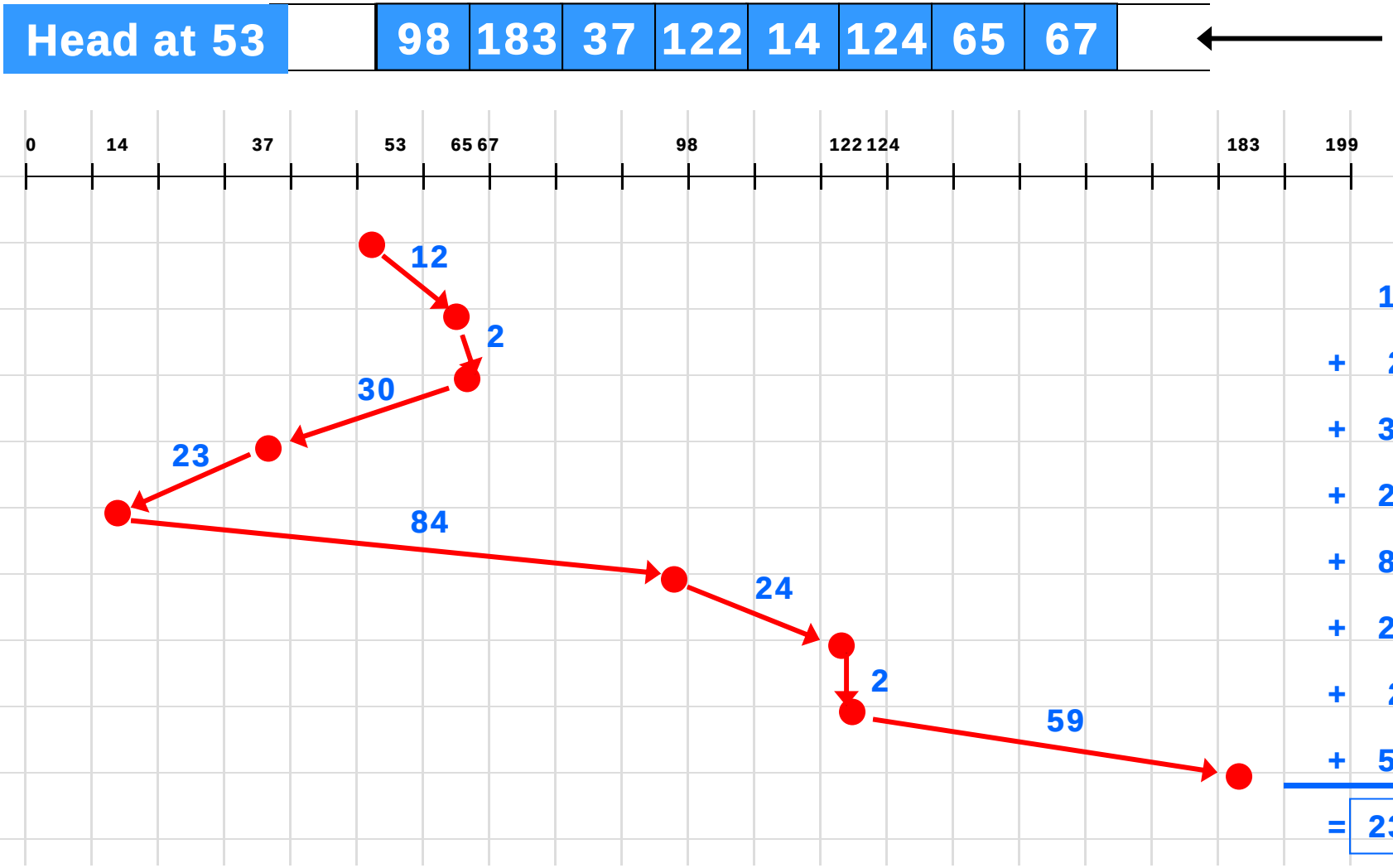
Disk Scheduling Algorithms(2)

- LOOK / C-LOOK
  - Like SCAN/C-SCAN but only go as far as last request in each direction (not full width of the disk)
- In general, unless there are request queues, disk scheduling does not have much impact
  - Important for servers, less so for PCs
- Modern disks often do the disk scheduling themselves
  - Disks know their layout better than OS, can optimize better
  - If so, ignores/undoes any scheduling done by OS

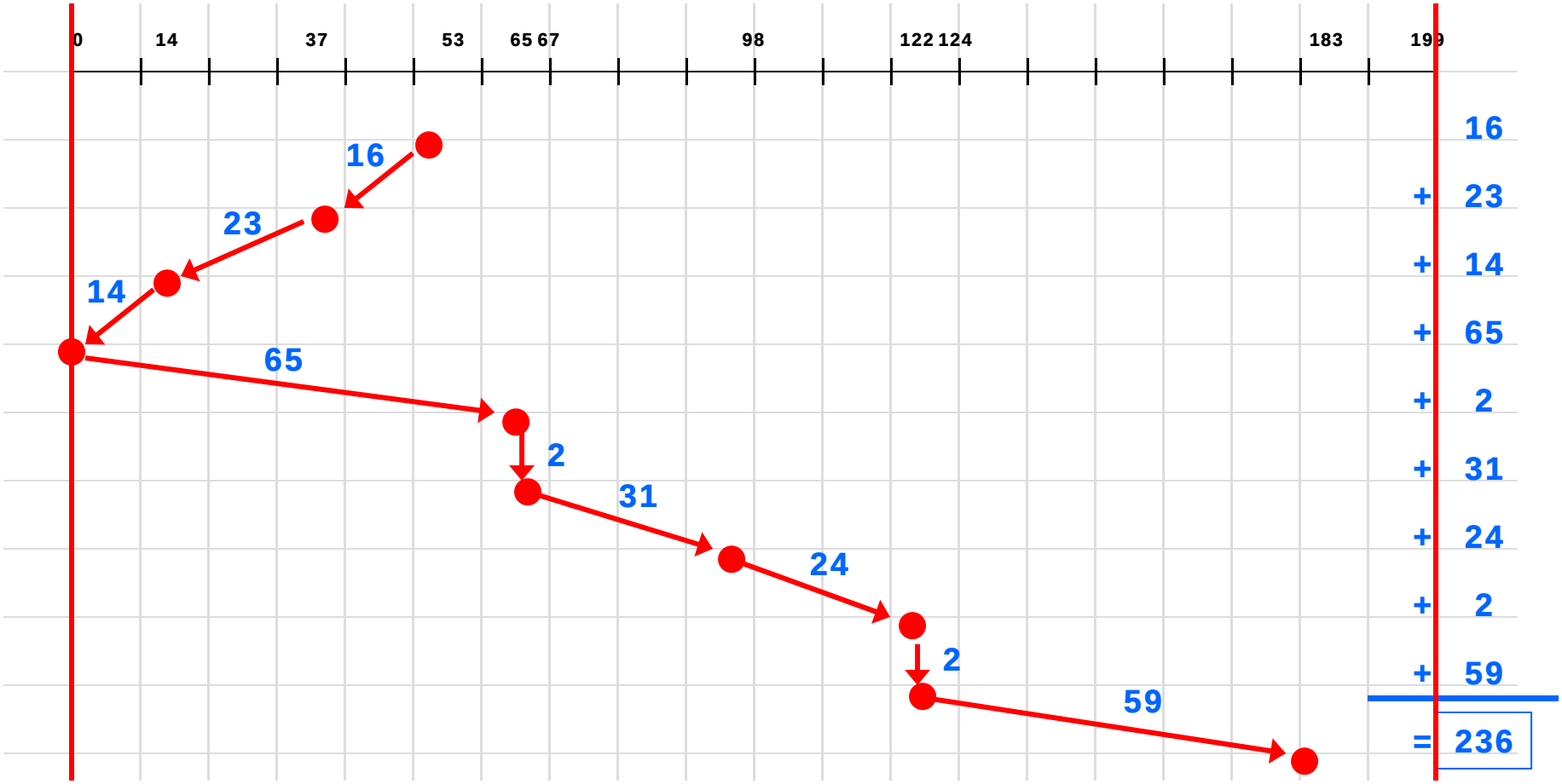
Example: FCFS



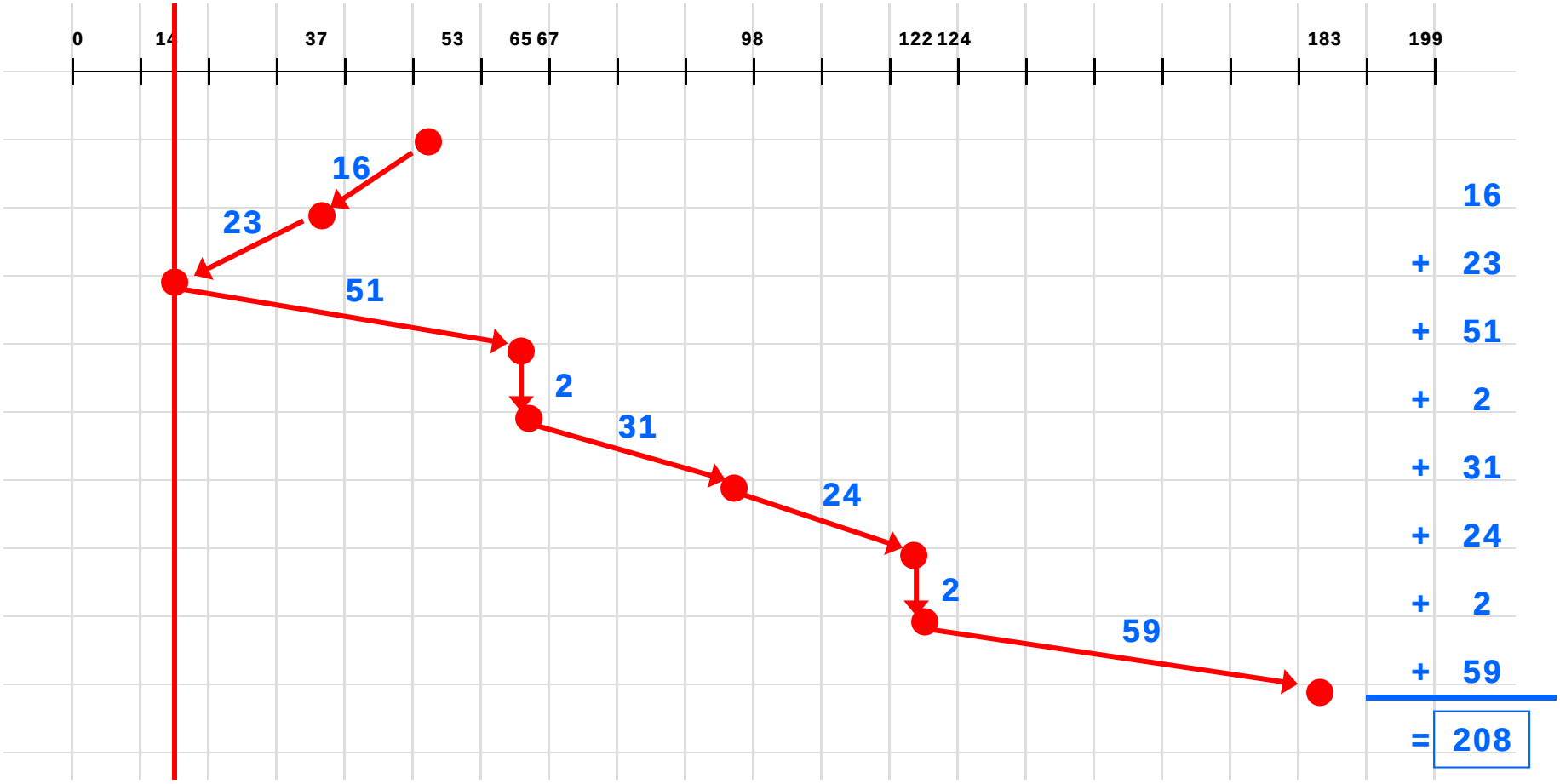
Example: SSTF



Example: Scan



Example: Look



Summary

- File systems overview
  - Disks are large, persistent, but slow
  - Operations on files and directories, sharing
- File system organization
  - VSFS example, ext2, other strategies and design choices
- Performance enhancements: caching, read-ahead
- Disks
  - Physical structure
  - Placement problems and strategies, FFS
  - Disk scheduling algorithms

Next time…

- More on File Systems
- Examples of modern file systems
  - Log-structured file system
  - Ext3
  - NTFS (time permitting..)

Announcements

- Assignment 4!

- Three tutorial exercises to help you get started
  - Tutorial exercises 7 and 8 (due next week)
  - Tutorial exercise 9 (due the week after)
  - Work in pairs with your assignment partner (some code may be similar)
  - Start early, don't wait until the deadline for the exercises
    - If you do, you won't finish A4 on time!!