CSC369: Operating Systems

Fall 2014

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International Summer Research Projects

Summer research projects are an exciting opportunity to earn credit towards your degree while gaining hands-on lab experience with world-class researchers around the world.

There are spots available in Sweden (Lund), Hong Kong (CUHK), Wales (Cardiff), Singapore (NUS) and Saudi Arabia (KAUST) for Summer 2015.

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Application deadline extended to Nov 28.

For more information, please attend one of the info sessions below or email international.utm@utoronto.ca

IEC International Education Centre

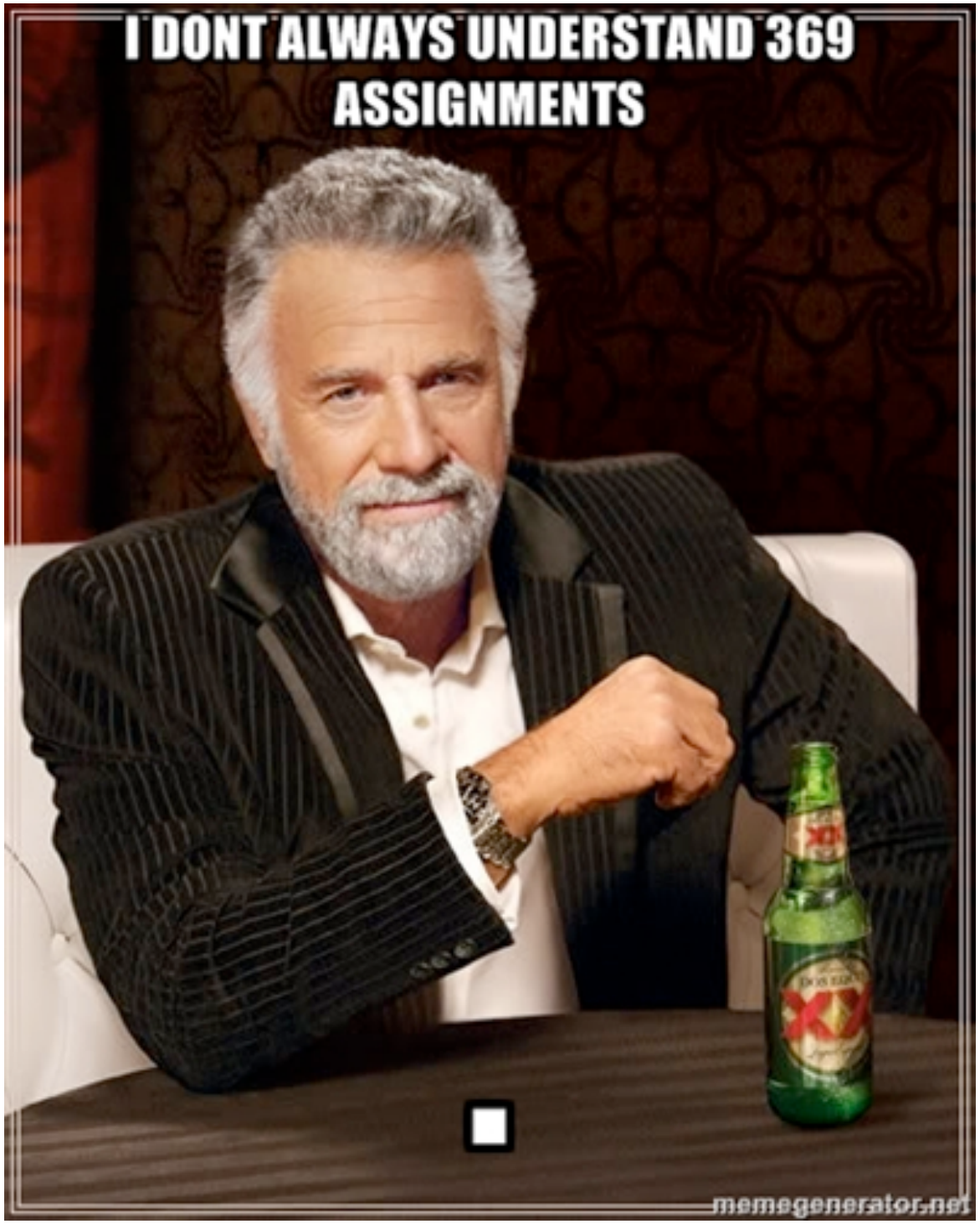
Info Sessions - Tuesday November 18	
10:00 – 11:00	DV 1160
2:00 – 3:00	DV 1158A

Anonymous Says ...

What is up with all the paragraph writing?

- Writing -- communicating your ideas clearly and succinctly -- is important.
- Perhaps more important than anything else we do.

Past A3 Commentary ...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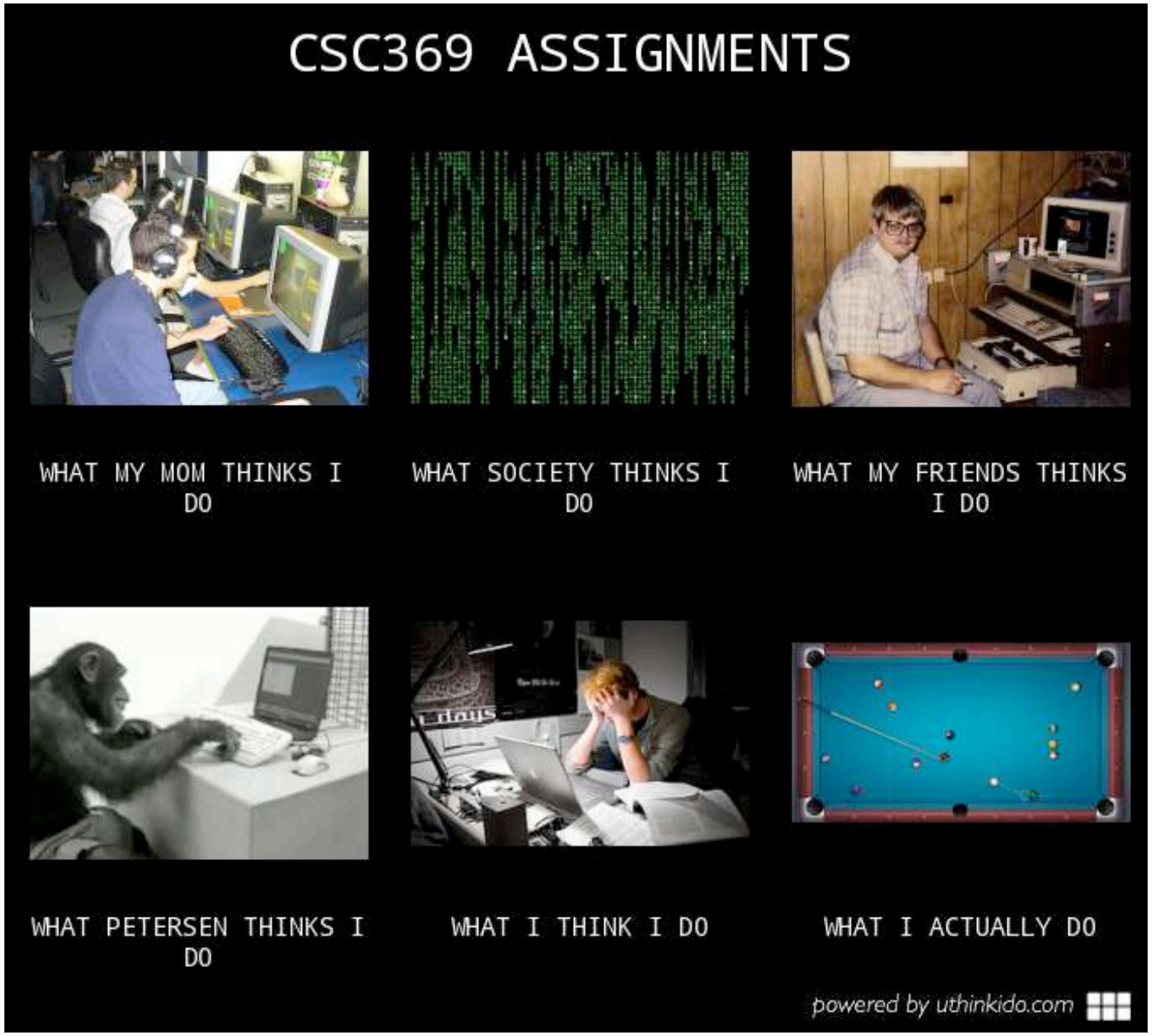
memegenerator.net



Anonymous, please take a bow.

Outline

- Inodes
- Traversing Paths
- Disk layout

Making Sense of Ext2

- The file system sees storage as linear array of blocks
  - Each block has a logical block number (LBN)

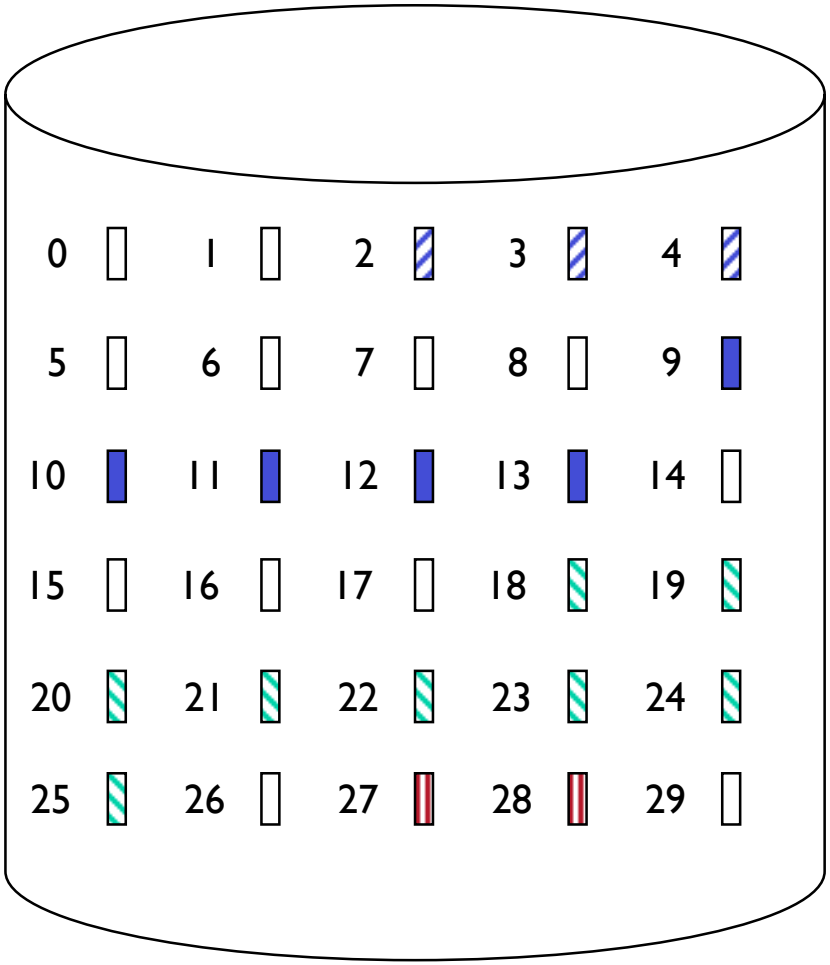
Directory Implementation

- Option 1: List
  - Simple list of file names and pointers to data blocks
  - Requires linear search to find entries
  - Easy to implement, slow to execute
    - And directory operations are frequent!
- Option 2: Hash Table
  - Create a list of file info structures
  - Hash file name to get a pointer to the file info structure in the list
  - Hash table takes space

Disk Layout Strategies

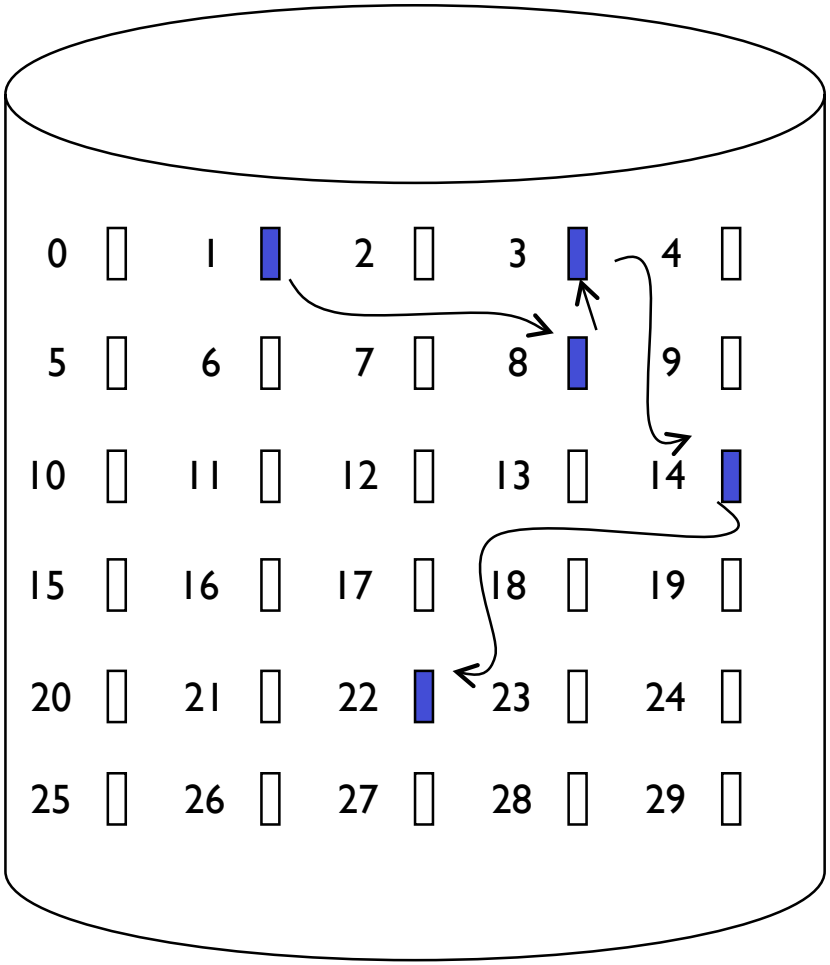
- Files often span multiple disk blocks (think "processes often span multiple pages ...")
- How do you find all of the blocks for a file?
  1. Contiguous allocation
     - Fast, simplifies directory access and allows indexing
     - Inflexible, causes external fragmentation, requires compaction
  2. Linked, or chained, structure
     - Each block points to the next, directory points to the first
     - Good for sequential (streaming) access, bad for all others
  3. Indexed structure (kind of like address translation)
     - An "index block" contains pointers to many other blocks
     - Handles random access better, still good for sequential
     - May require multiple, linked index blocks

Contiguous Allocation



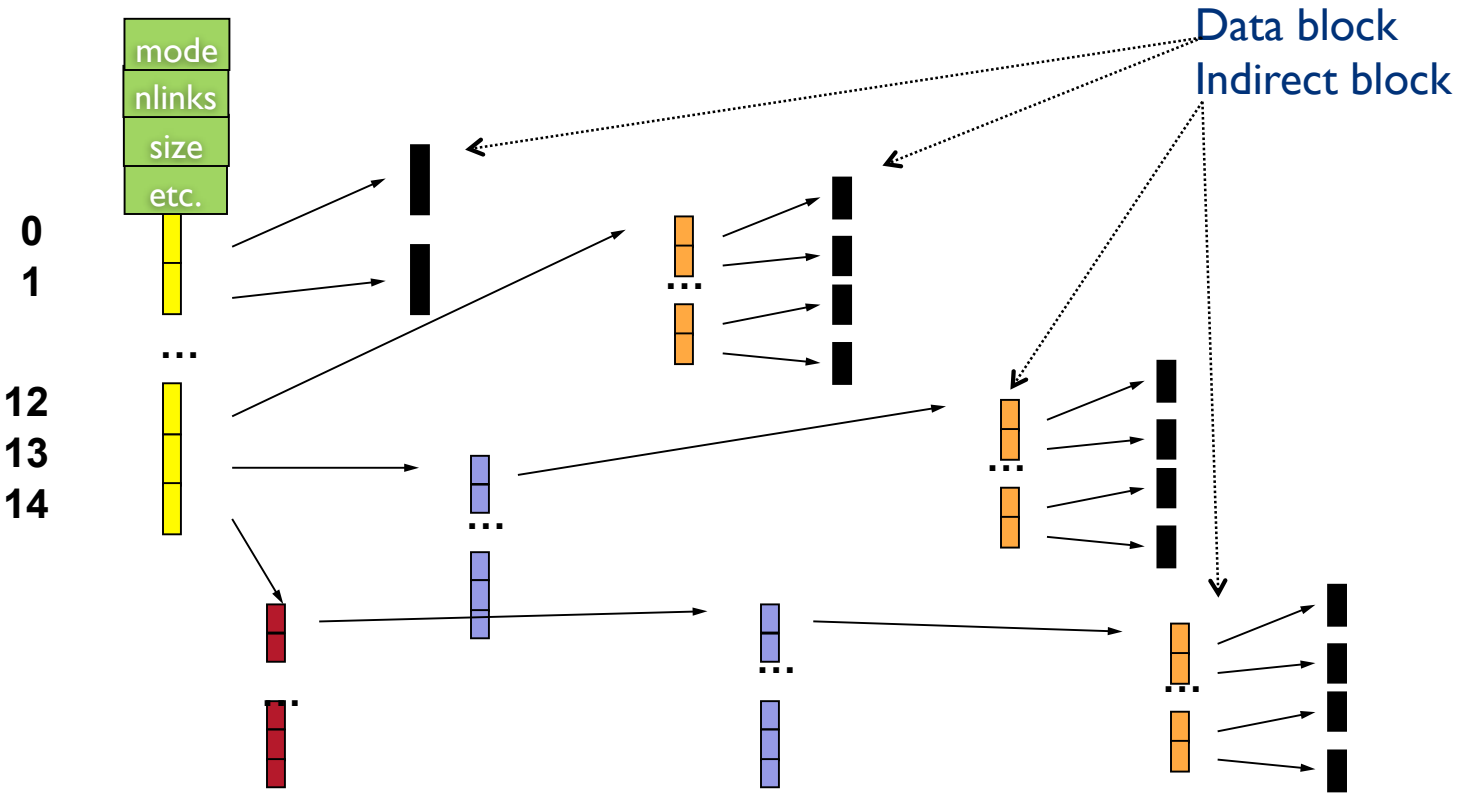
File Name	Start Blk	Length
File A	2	3
File B	9	5
File C	18	8
File D	27	2

Linked Allocation



File Name	Start Blk	Last Blk
…	…	…
File B	1	22
…	…	…

Indexed: UNIX Inodes



Indexed Allocation: Unix Inodes

- Unix inodes implement an indexed structure for files
- All file metadata is stored in an inode
  - Unix directory entries map file names to inodes
- Each inode contains 15 block pointers
  - First 12 are direct block pointers
    - Disk addresses of first 12 data blocks in file
  - The 13th is a single indirect block pointer
    - Address of block containing addresses of data blocks
  - Then the 14th is a double indirect block pointer
    - Address of block containing addresses of single indirect blocks
  - Finally, the 15th is a triple indirect block pointer

Outline

- Inodes
- Traversing Paths
- Disk layout

Path Name Translation

- Let's say you want to open "/one/two/three"
- What does the file system do?
  - Open directory "/" (the root, well known, can always find)
  - Search for the entry "one", get location of "one" (in directory entry)
  - Open directory "one", search for "two", get location of "two"
  - Open directory "two", search for "three", get location of "three"
  - Open file "three"

- Systems spend a lot of time walking directory paths
  - This is why open is separate from read/write
  - OS will cache prefix lookups for performance

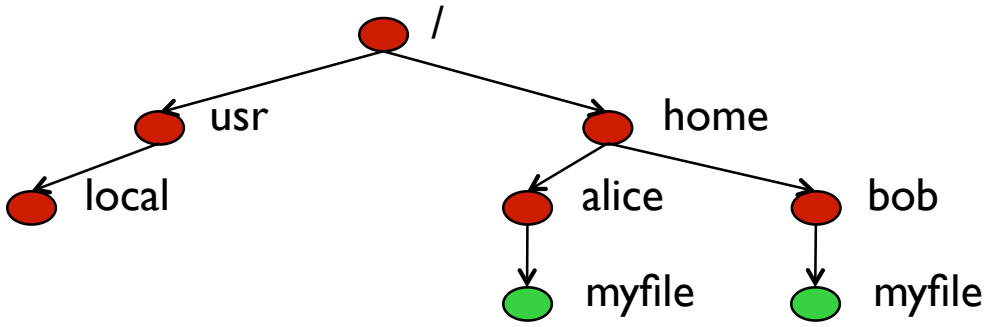
Inodes and Path Search

- Unix Inodes are not directories
  - Directories are files that impose logical organization
  - Inodes are structures that impose physical organization --where on the disk the blocks for a file are placed
- Directory entries map file names to inodes
  - To open "/one", use the master block to find the inode for "/" on disk and read the inode into memory
  - The inode allows us to find data block for directory "/"
  - Read "/", look for entry for "one"
  - This entry gives location of the inode for "one"
  - Read the inode for "one" into memory
  - The inode for "one" says where first data block is on disk
  - Read that block into memory to access the data in the file

Current Working Directory

- The current working directory is used as a base for specifying file names
  - Relative path or file names are specified with respect to current directory
  - Absolute names start from the root of directory tree
- Special names are used to navigate up and down the hierarchy: "." == current directory, ".." == parent

- If the working directory is */home/bob*, how can we refer to *myfile* in alice's directory?



Outline

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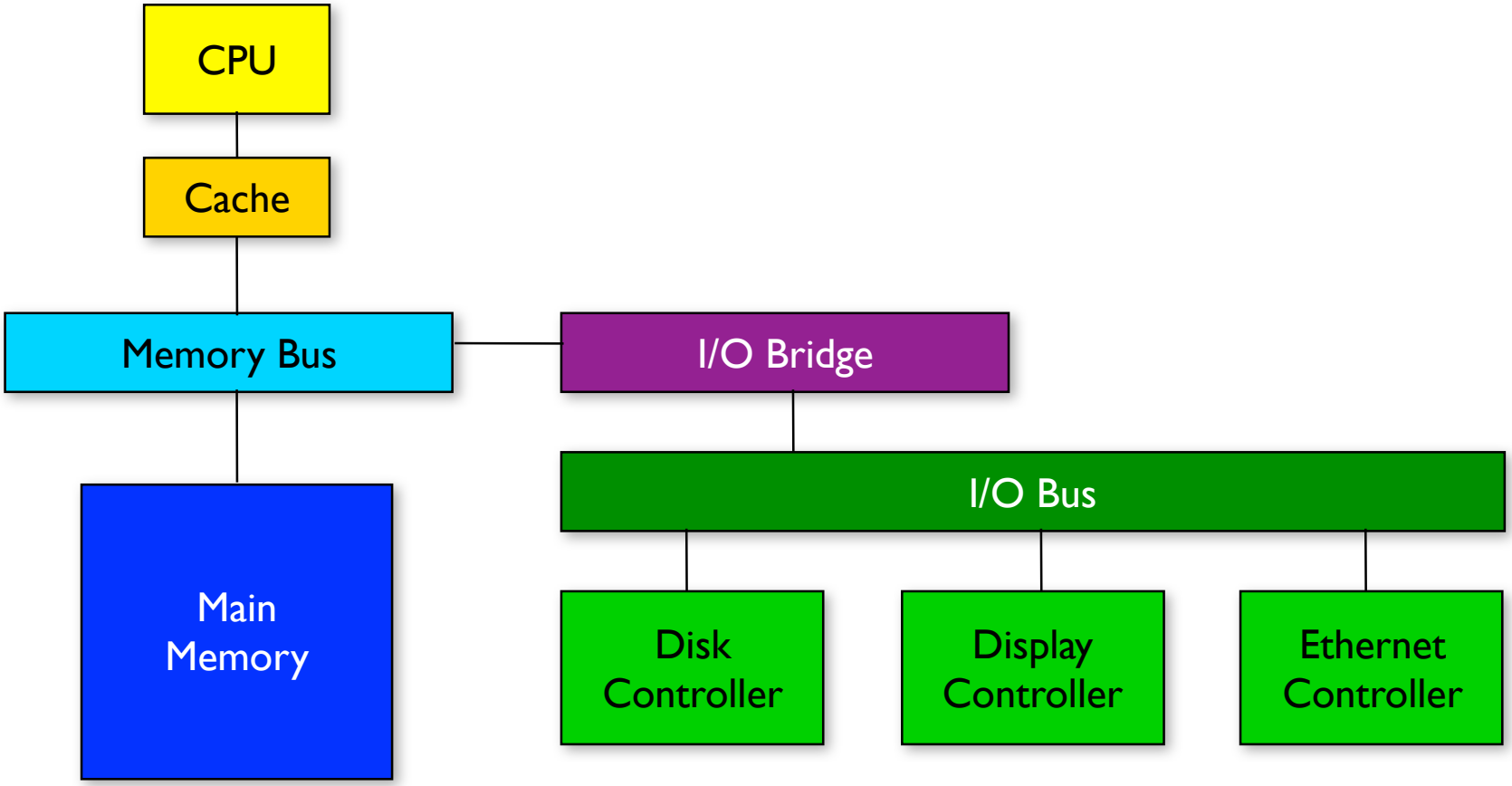
So … Why are Disks Slow?

- We have asserted that writes to disk are slow
  - Specifically, writes to multiple small locations are worse than a single write
  - This is a result of the disk technology being used!
- This means that he policy decisions we're making are based on available technology
  - … and the technology is changing

I/O Diagram


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

Secondary Storage

- Secondary storage is usually:
  - Anything outside of "primary memory"
  - Anything that does not permit direct instruction execution or data fetch via machine load/store instructions
- Characteristics
  - It's large – hundreds of megabytes, gigabytes, terabytes
  - It's cheap - 500GB internal for $110 (CAN$)
  - It's persistent – data survives loss of power
  - It's slow – milliseconds to access (is a millisecond slow?)

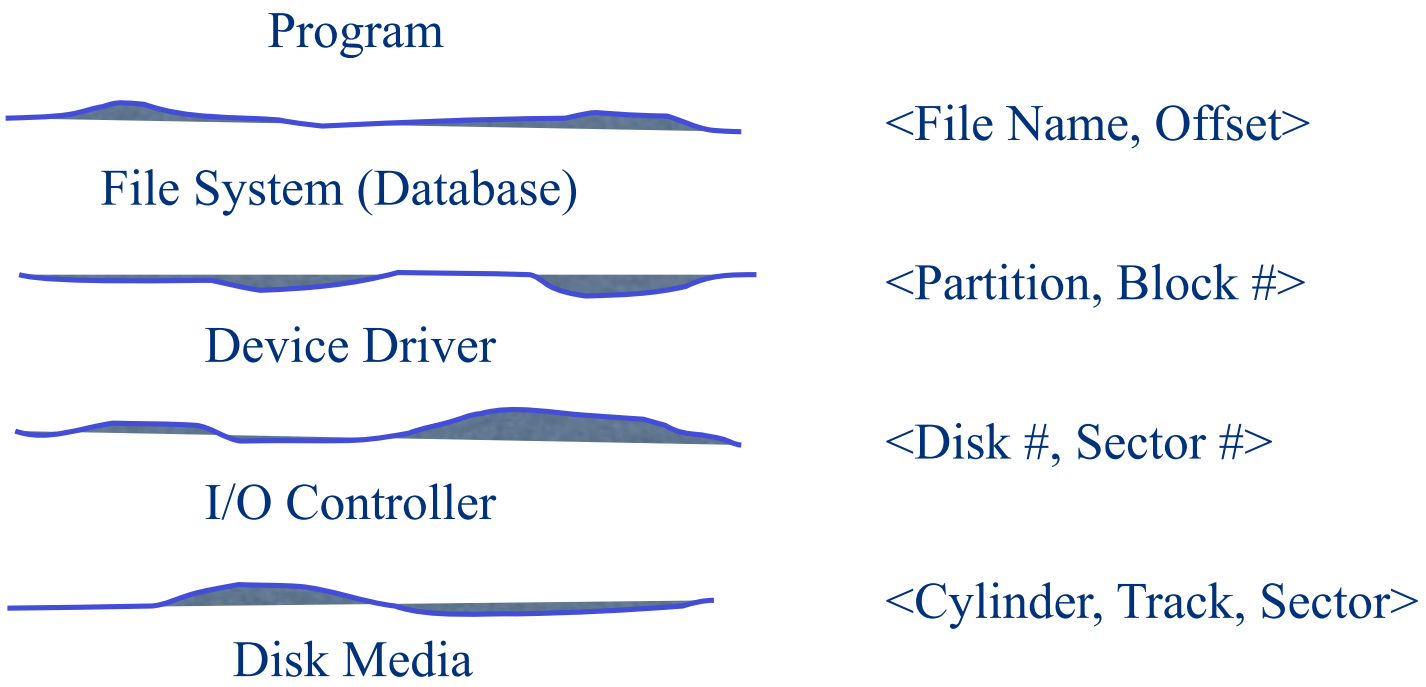
Secondary Storage Devices

- Drums: ancient history
- Magnetic disks
  - Fixed and removable (floppy -- also ancient history)
- Optical disks
  - Write-once, read-many (CD-R, DVD-R)
  - Write-many, ready-many (CD-RW)
- Solid state devices
  - These do not have many of the limitations that have caused OS policy to be as it is!
- To understand how we got to where we are, focus on the use of magnetic disks for implementing secondary storage

Disk Abstraction

- 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

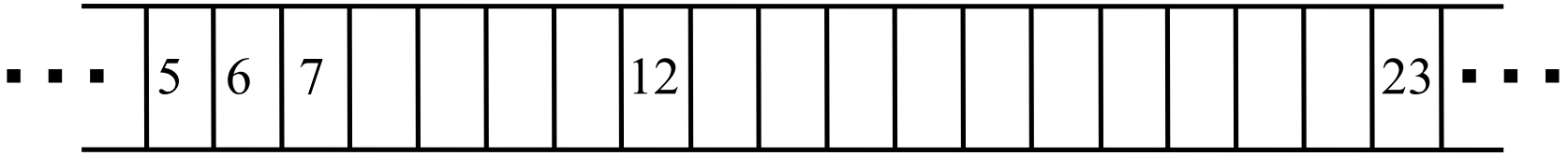


- Each layer abstracts details below it for the layers above it
  - Naming and address mapping
  - Caching and request transformations

Disk Interaction

- Specifying disk requests requires a lot of info:
  - Cylinder #, surface #, track #, sector #, transfer size…
    - Older disks required the OS 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, for example)
  - Kind of like an OS on the device, so disk parameters are hidden from system OS
  - 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

Common Storage Device Interface

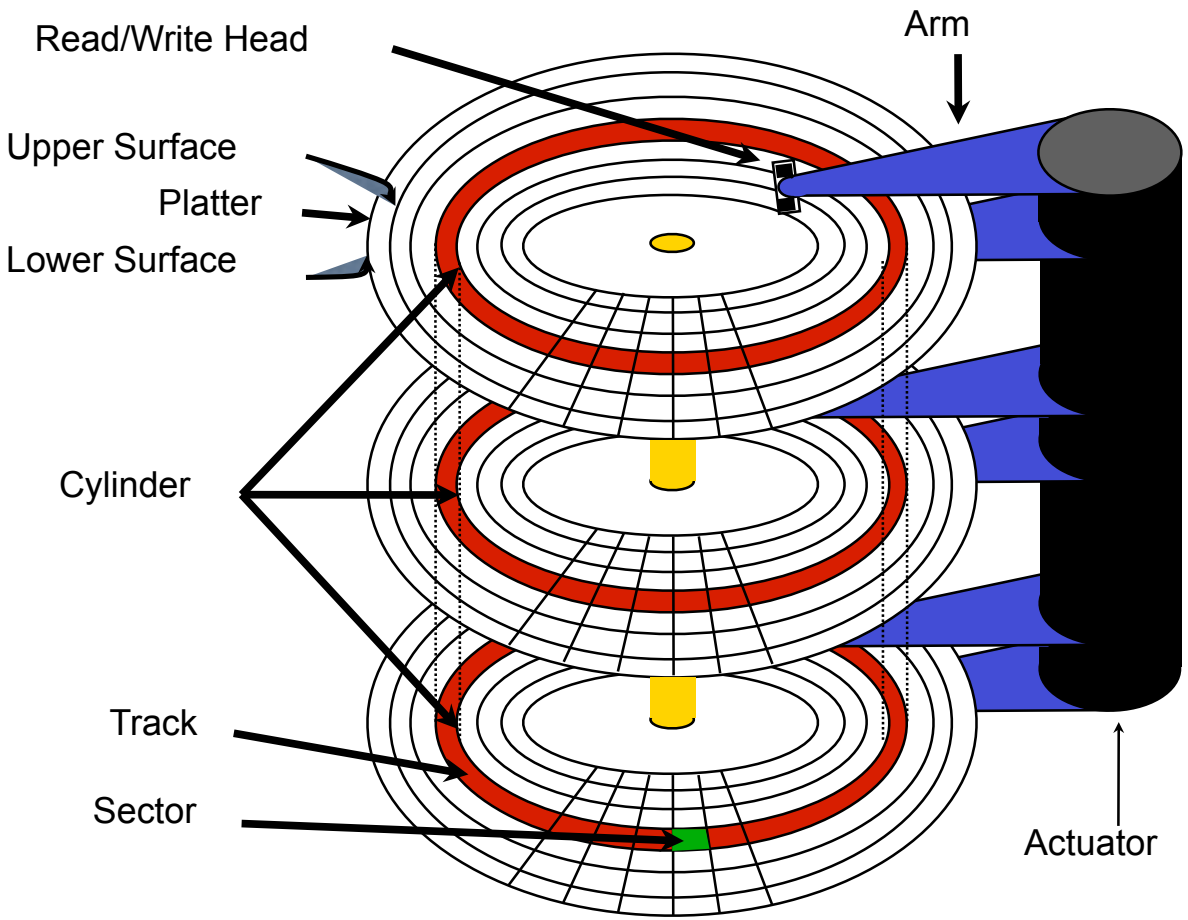


OS's view of storage device

Storage exposed as linear array of blocks

- Common block size: 512/1024/4096 bytes
- Number of blocks: device capacity / block size

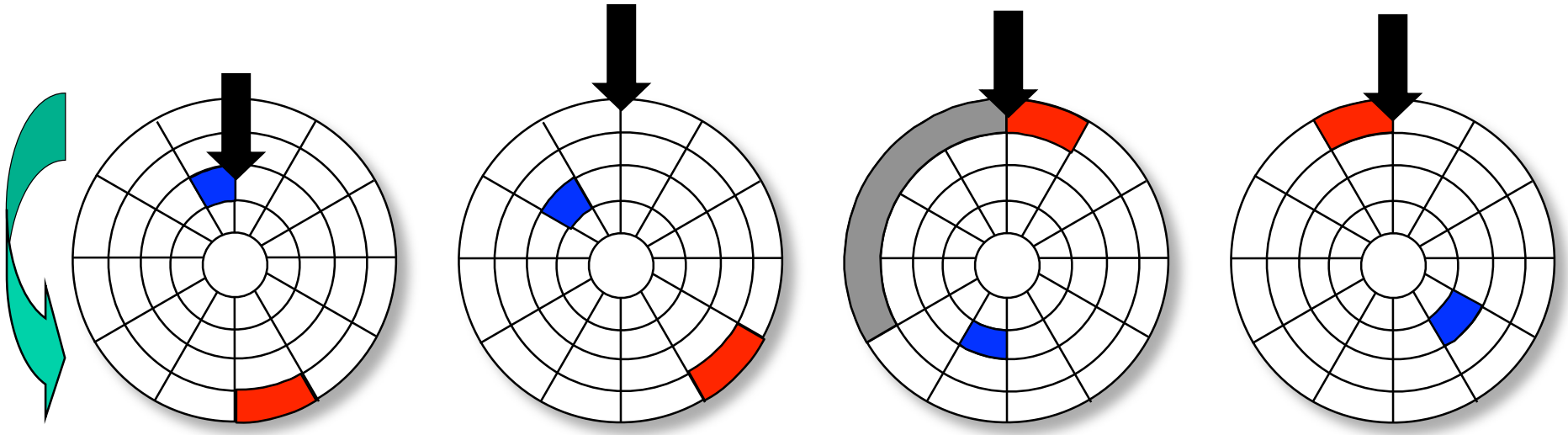
Disk Components



Disk Performance

- Disk request performance depends upon a number of steps
  - Seek – moving the disk arm to the correct cylinder
    - Depends on how fast disk arm can move (increasing very slowly)
  - Rotation – waiting for the sector to rotate under the head
    - Depends on rotation rate of disk (increasing, but slowly)
  - Transfer – transferring data from surface into disk controller electronics, sending it back to the host
    - Depends on density (increasing quickly)

Disk Latency Example



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

Disk Scheduling

- The OS tries to schedule disk requests that are queued waiting for the disk
  - FCFS (no optimization)
    - Reasonable when load is low
    - Long waiting times for long request queues
  - SSTF (shortest seek time first)
    - Minimizes arm movement (seek time), maximizes request service rate
    - Favors middle blocks
  - SCAN (elevator), C-SCAN
    - Service requests in one direction until done, then reverse
    - C-SCAN only goes in one direction (like a typewriter)

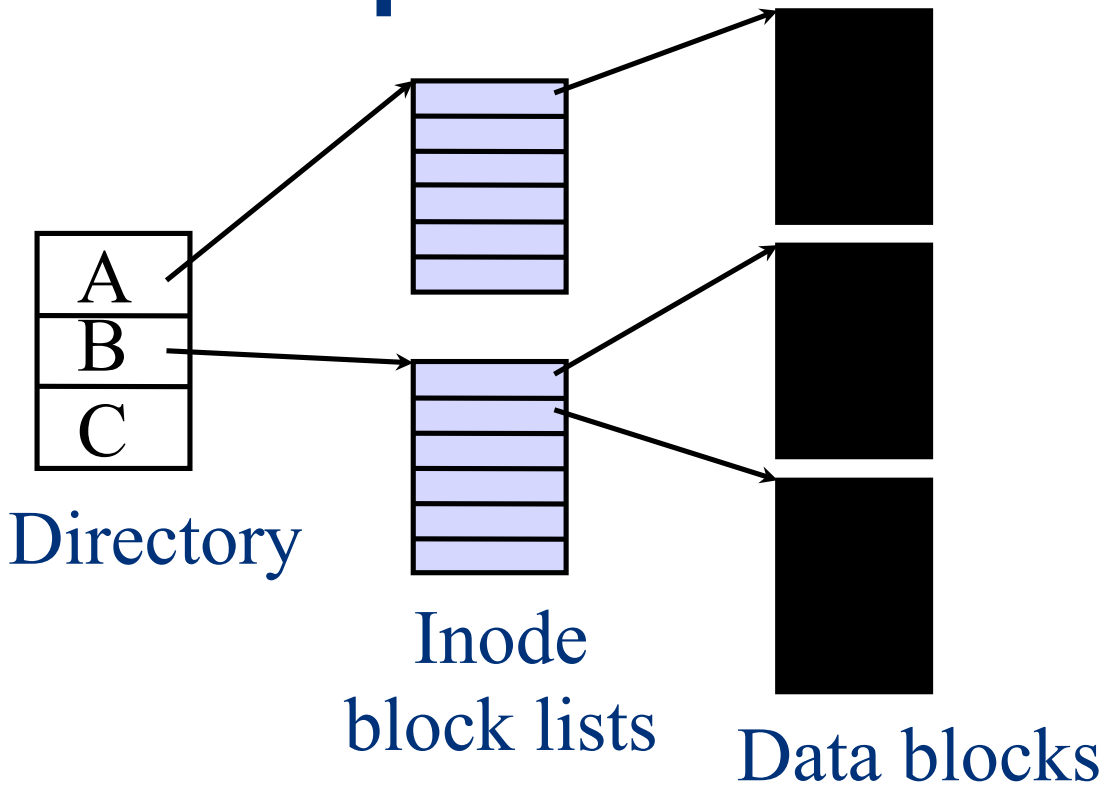
Disk Scheduling, continued

- 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

Optimizing Disk Performance

- Done best where disk management happens
- High-level disk characteristics yield two goals:
  - Closeness
    - Reduce seek times by placing related data close
    - Benefits can be in the factor of 2 range
  - Amortization
    - Amortize each positioning delay by fetching lots of data
    - Benefits can reach into the factor of 10 range
    - Ex: prefetching

Inodes: Indirection & Independence



- File size grows dynamically, allocations are independent
- Difficult to achieve closeness and amortization

Original Unix File System

- The file system 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 (lots of seeking)

Data and Inode Placement

Original Unix FS had two placement problems:

1. Data blocks are allocated randomly in aging file systems
   - Blocks for the same file allocated sequentially when FS is new
   - As FS "ages" and fills, need to allocate into blocks freed up when other files are deleted
   - Problem: Deleted files are essentially randomly placed, so new allocations are scattered
2. Inodes are allocated far from blocks
   - All inodes at beginning of disk, far from data
   - Traversing file name paths, manipulating files, directories requires going back and forth from inodes to data blocks

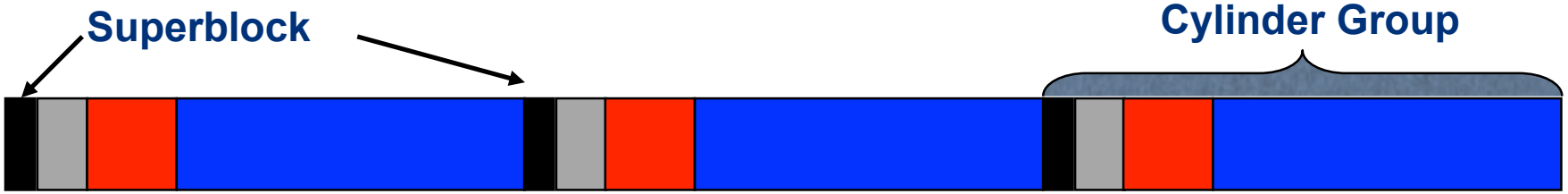
Both of these problems generate many long seeks

FFS

- BSD Unix 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
- Now the FS from which all other Unix FS's have been compared
- Good example of being device-aware for performance

Cylinder Groups

- BSD FFS addressed placement problems using the notion of a cylinder group (allocation group)
  - 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 allocated in same cylinder group as file data blocks



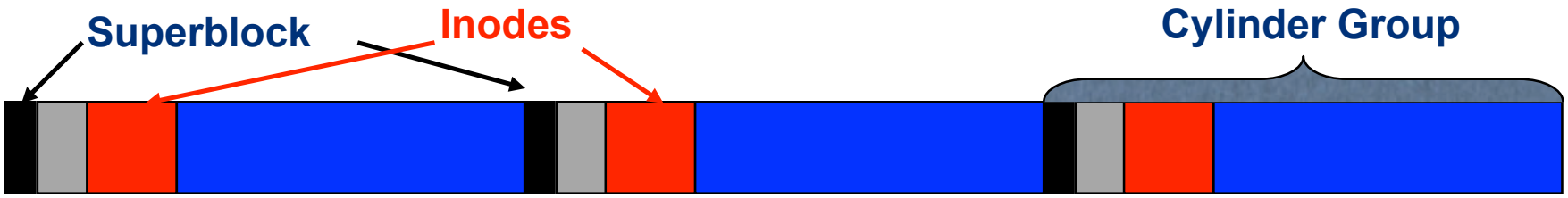
Cylinder group organization

Cylinder Groups

- 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 this purpose
    - Only used by root – this is why it is possible for "df" to report >100%
  - If preferred cylinder group is full, allocate from a "nearby" group

FFS: Consistency Issues

- Inodes: fixed size structure stored in cylinder groups



- Metadata updates should be atomic operations:
  - Write newly allocated inode to disk before its name is entered in a directory.
  - Remove a directory name before the inode is deallocated
  - Write a deallocated inode to disk before its blocks are placed into the cylinder group free list.

Solving Consistency Problems

- If the server crashes during any of these operations, then the file system is in an inconsistent state.
- Solution:

  Keep a log of updates to enable roll-back or roll-forward.

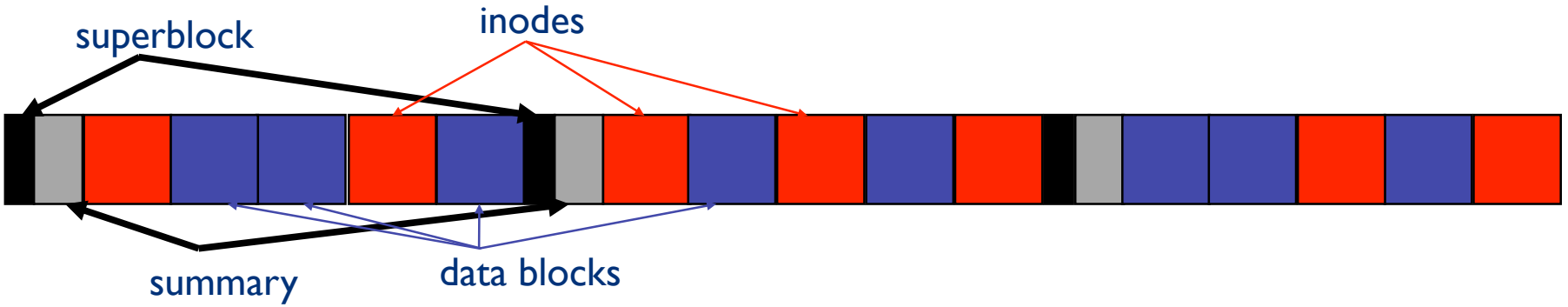
Are Reads the Problem?

- Observation: Most of the reads that go to the disk are the first read of a file. Subsequent reads are satisfied in memory by the file buffer cache.

- There is no performance problem with reads (except the first). Writes are the problem.
- Writes are not well-clustered, as they include modifying inodes and data blocks.

Log Structured File System (LFS)

- Developed by Ousterhout in 1989
- Idea: Write ***all*** file system data in a continuous log
- Uses inodes and directories from FFS
- Needs an inode map to find the inodes
- Cleaner reclaims space from overwritten or deleted blocks.



LFS Reads

- If the writes are easy, what happens to the reads?
- To read a file from disk:
  1. Read the superblock to find the index file
  2. Read the index file and find the inode-map
  3. Get the file's inode
  4. Use the inode as usual to find the file's data blocks
- Remember, we expect reads to hit in memory most of the time … after we open the file in the first place.

In practice?

- Cleaning turns out to be quite complicated
  - The "tail" of the log must always be moved up to give the "head" space to read
  - Depending on when cleaning happens there may be significant performance loss.
- LFS inspired the logging features of journaling file systems in use today. e.g., Ext3.
  - Old and new versions of data are kept on disk until update is complete
  - For undo capabilities write old data to log, and for redo, write new data to the log
  - A commit operation releases data from the log
  - Each file operation is a transaction

Summary

- Secondary storage is generally large, persistent, and relatively slow
- File system policies have been influenced by the limitations of the hardware implementation
  - Even after those limitations are removed, some of the policies remain
- We focused on magnetic disks, since those drove the development of advanced file allocation policies
  - The key: Accessing non-contiguous blocks is slow!
  - FFS and LFS are attempts to reduce non-contiguous access time