CSE 120
Principles of Operating Systems

Spring 2023

Lecture 15: File System Disk Layout

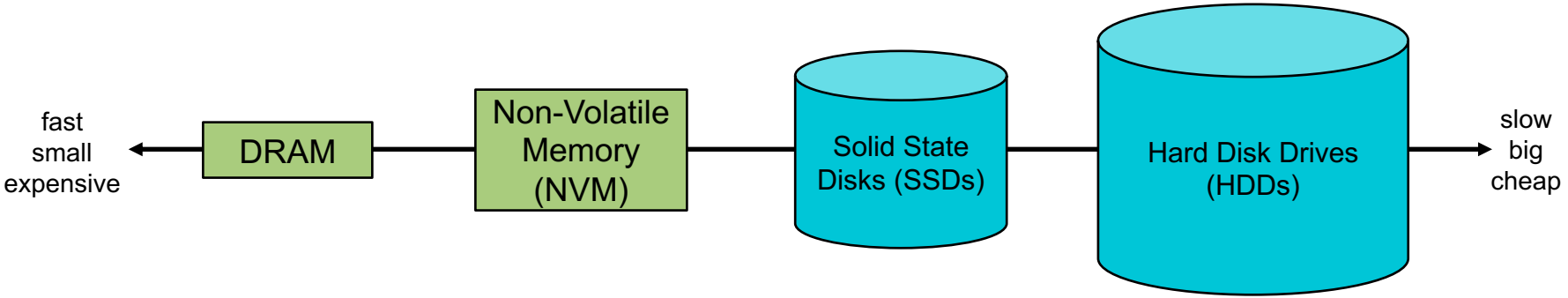
Amy Ousterhout

Administrivia

- Homework #4
  - Due Tuesday June 6th
- Project 3
  - Deadline to change teams: today
  - Due June 10th – there will be no extensions
  - Get started early!

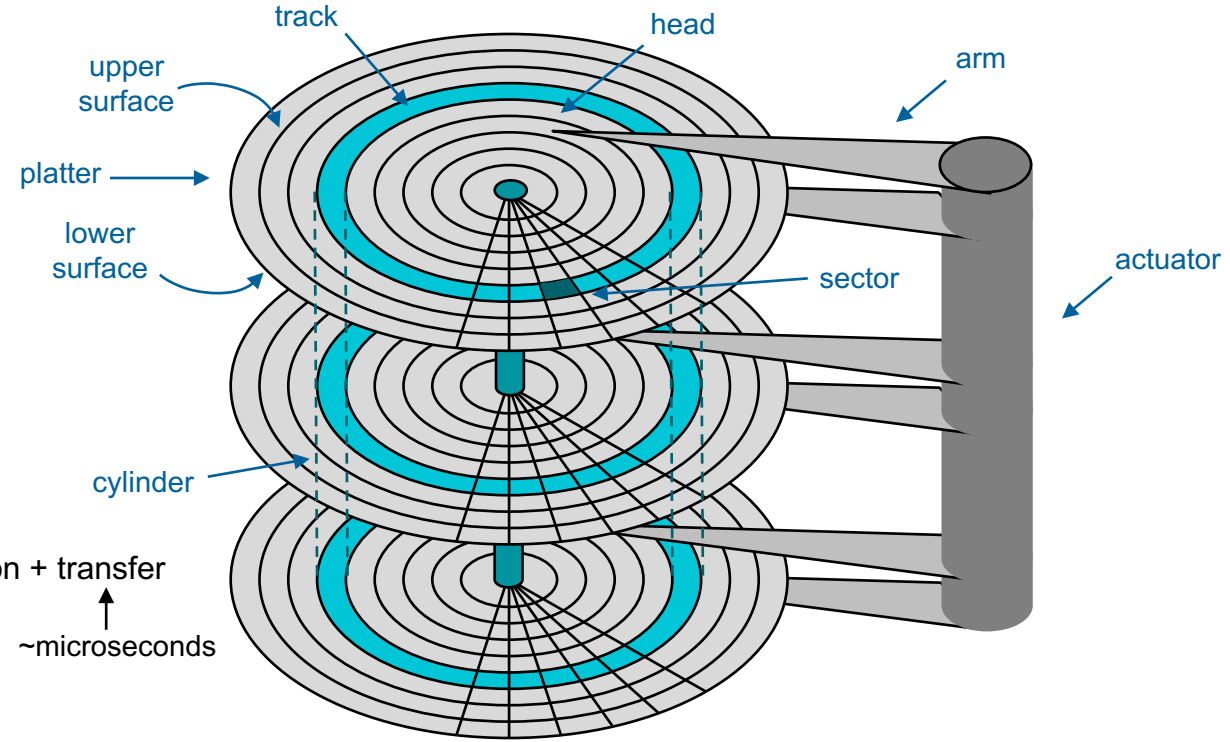
Memory and Storage Technologies

- Tradeoffs between latency, bandwidth, capacity, and cost



Latency:	50-100 ns	300 ns	20-100 µs	5-10 ms
Bandwidth:	50-100 GB/s	a few GB/s	a few GB/s	100-150 MB/s
Capacity:	tens of GB per DIMM	tens – hundreds of GB per DIMM	64 GB – 4 TB	1-8 TB
Cost:	$$$$	$$$	$$	$

Hard Disks

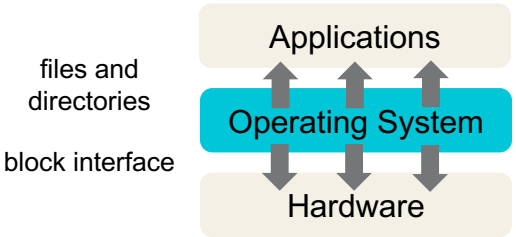


Disk latency = seek + rotation + transfer

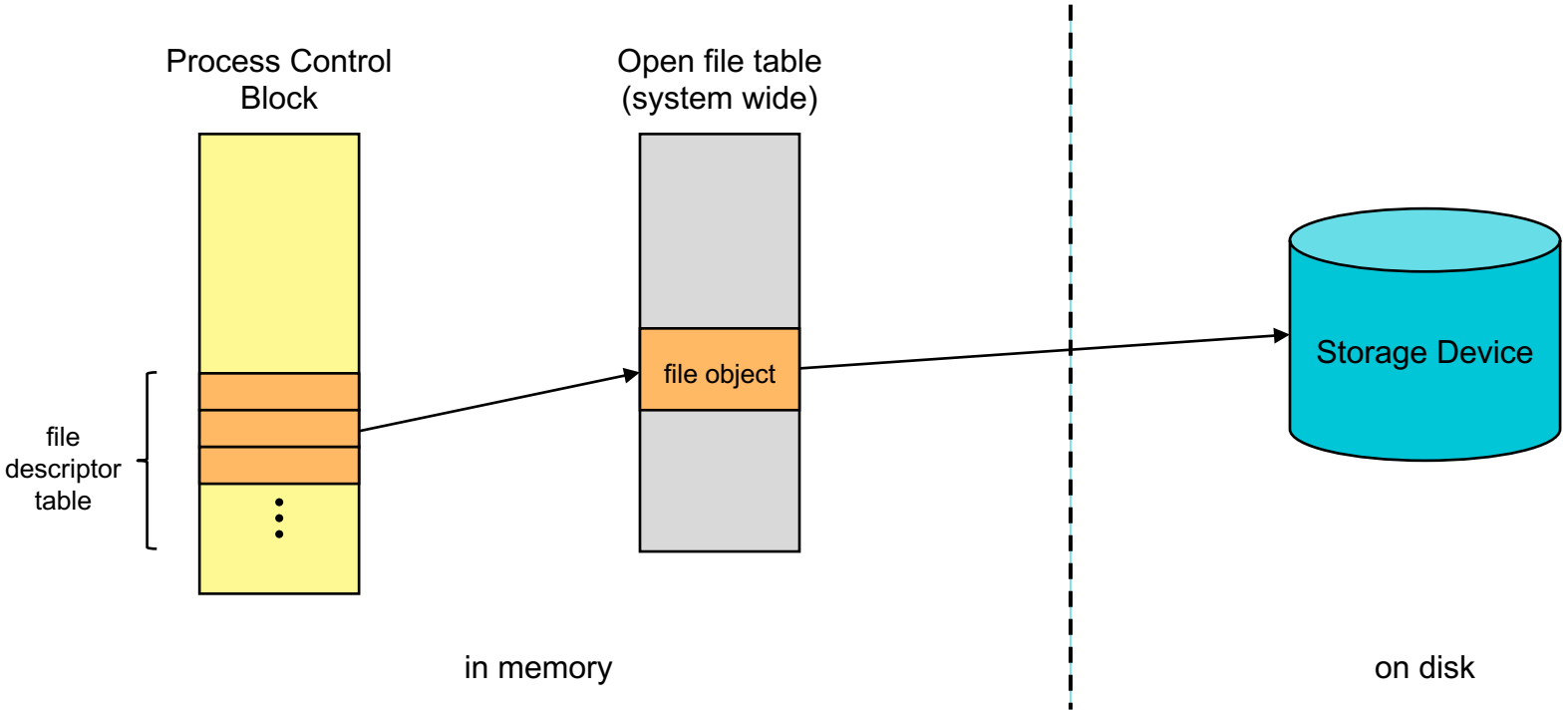
~milliseconds ~microseconds

File System APIs

- API between the OS and storage devices
  - Block interface: disk maps logical blocks to surface/track/sector
  - OS refers to blocks by their number
- API between the OS and applications
  - File: a named collection of bytes
  - Directory: a way to organize files logically



Typical File System Data Structures

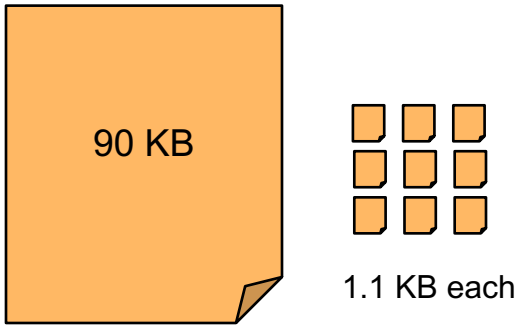


File System Challenges

- Files grow and shrink
  - Little a priori knowledge
  - 6-8 orders of magnitude in file sizes
- Disk performance behavior
  - Highly nonuniform access
  - Efficiency can be challenging
- Failures

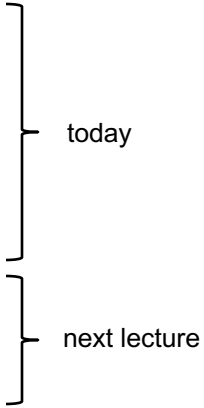
File System Workloads Motivate Design

- Workloads can influence the design of a file system
- File characteristics (measurements of UNIX and NT)
  - Most files are small (about 8KB)
  - Most of the disk is allocated to large files
    - » 90% of data is in 10% of files
- Access patterns
  - Sequential vs. random
  - Access files in the same directory together
    - » Spatial locality
  - Access metadata at the same time as the file
    - » Need metadata to find data



Key Questions

- How do we keep track of blocks used by a file?
- Where do we store metadata information?
- How do we (really) do path name translation?
- How do we implement common file operations?
- How can we cache data to improve performance?
- How can we handle disk crashes properly?



Today's Outline

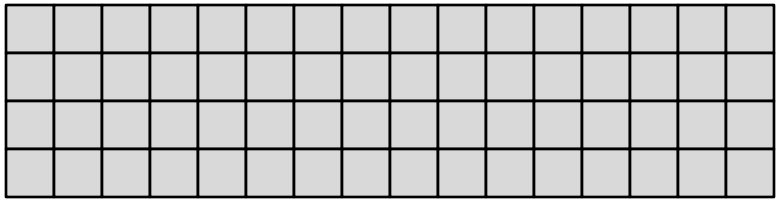
- File system layout
  - Managing disk space
  - Metadata
  - Path name translation
- Common file operations
  - Hard links
  - Symbolic (soft) links
  - Create
  - Rename
  - Delete

File System Layout

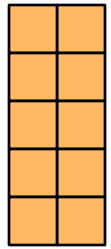
- We start with an empty disk

File System Layout

- Partition the disk into fixed-size file system blocks

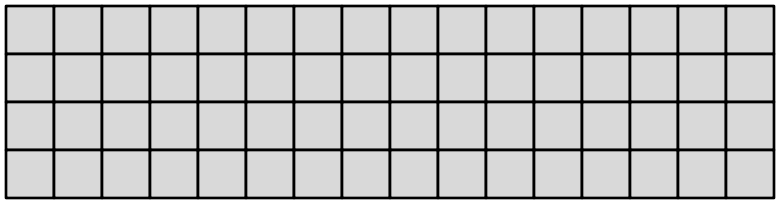


- Typically 4 KB in size
  - Block size is set when the file system is formatted
- Independent of disk physical sector size
  - If a sector is 512 bytes, file system will use 8 sectors/block
- One file can span multiple disk blocks (e.g., 40 KB file uses 10 blocks)
- A small file still uses an entire block



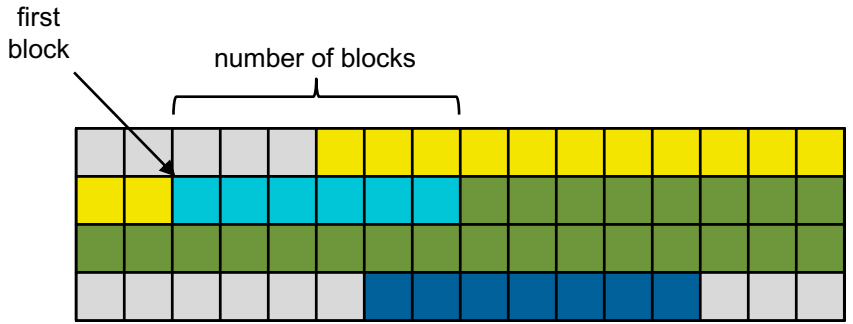
File System Layout

- How should we allocate blocks to files?
- How should we keep track of which blocks are for which file?
- We will consider several different approaches



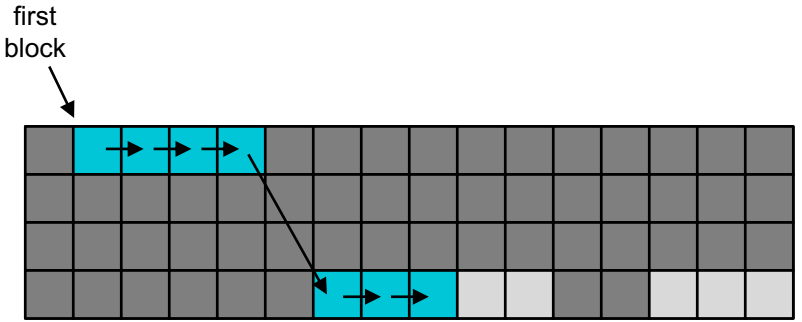
Contiguous Layout (or “extent-based”)

- Allocate a contiguous set of blocks to each file (e.g., IBM OS/360)
- File metadata:
  - Location of first block on disk
  - Number of blocks
- Pros:
  - Simple
  - Easy access, both sequential and random
  - Few seeks for I/O
- Cons:
  - Difficult to grow files
  - As files are created and deleted, fragmentation can occur



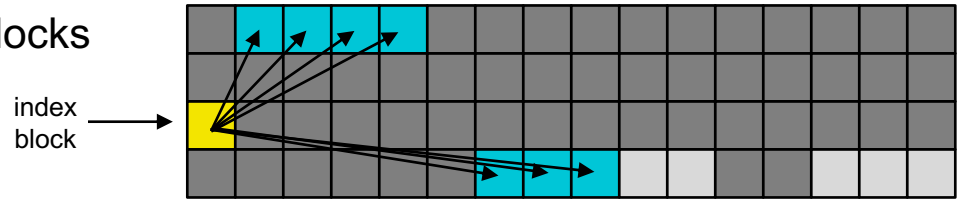
Linked Layout

- Allocate a linked list of blocks (e.g., Xerox Alto)
  - Essentially a linked list on disk per file
- File metadata:
  - Location of first block on disk
  - Each block contains a pointer to the next
- Pros:
  - Can grow files dynamically
  - No fragmentation
- Cons:
  - Random access is now slow
  - Sequential bandwidth may not be good
  - Unreliable: losing one block means losing the rest



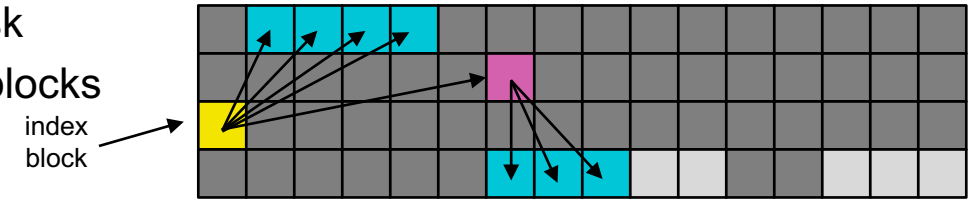
Indexed Layout

- Use a special index block to store pointers to the data blocks
- File metadata:
  - Location of the index block on disk
  - Index block contains pointers to blocks
- Pros:
  - Can grow files dynamically
  - No fragmentation
  - Easy random access (after reading the index block)
- Cons:
  - What if one index block is not big enough?
  - Sequential bandwidth may still not be good



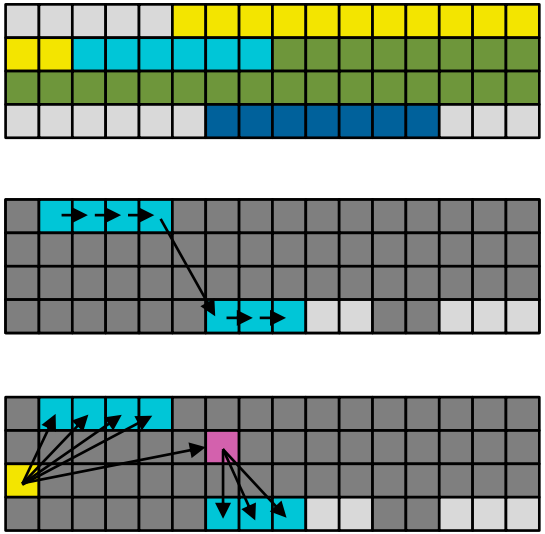
Multi-Level Indexed Layout

- Use a special index block to store pointers to the data blocks and indirect blocks to store more pointers to data blocks
- File metadata:
  - Location of the index block on disk
  - Index block contains pointers to blocks and indirect blocks
- Pros:
  - Can support much larger files
- Cons:
  - There is still a limit on the maximum file size
  - Sequential bandwidth may still not be good



Disk Layout Summary

- Files span multiple disk blocks
- Where are the blocks for a file located?
  - Contiguous allocation
    - » Fast, simplifies directory access
    - » Inflexible, causes fragmentation, needs compaction
  - Linked structure
    - » Each block points to the next, directory points to the first
    - » Random access is slow
  - Indexed structure (indirection, hierarchy)
    - » An “index block” contains pointers to many other blocks
    - » Handles random better
    - » May need multiple index blocks

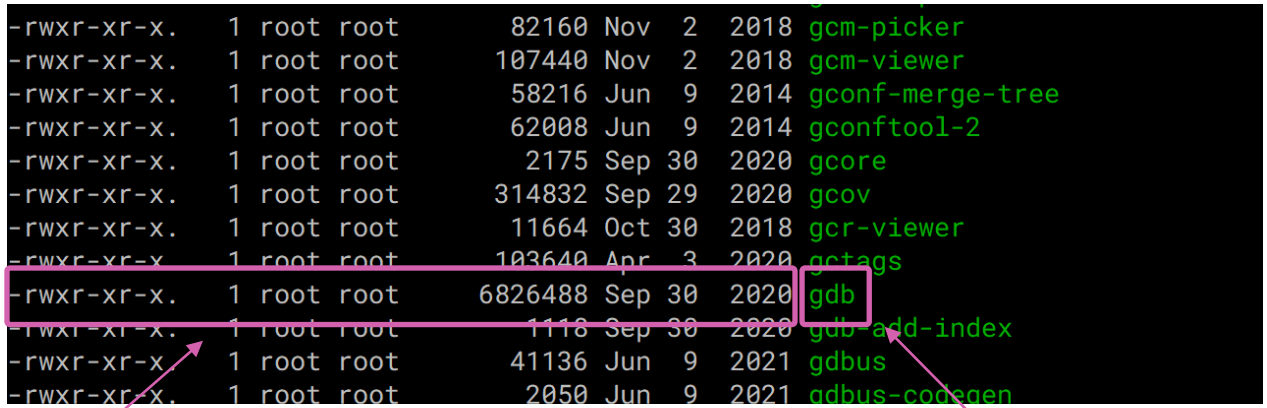


Unix Inodes

- Each file is associated with an inode (index node) on disk
  - Each inode has a unique inode number
- An inode stores all the metadata for a file:
  - All the data blocks of the file can be found from its inode
  - File size (in bytes and blocks)
  - User and group of file owner
  - Protection bits
    - » User/group/other, read/write/execute
  - Link count
    - » How many directory entries point to this inode
  - Timestamps
    - » Created, modified, last accessed, any change

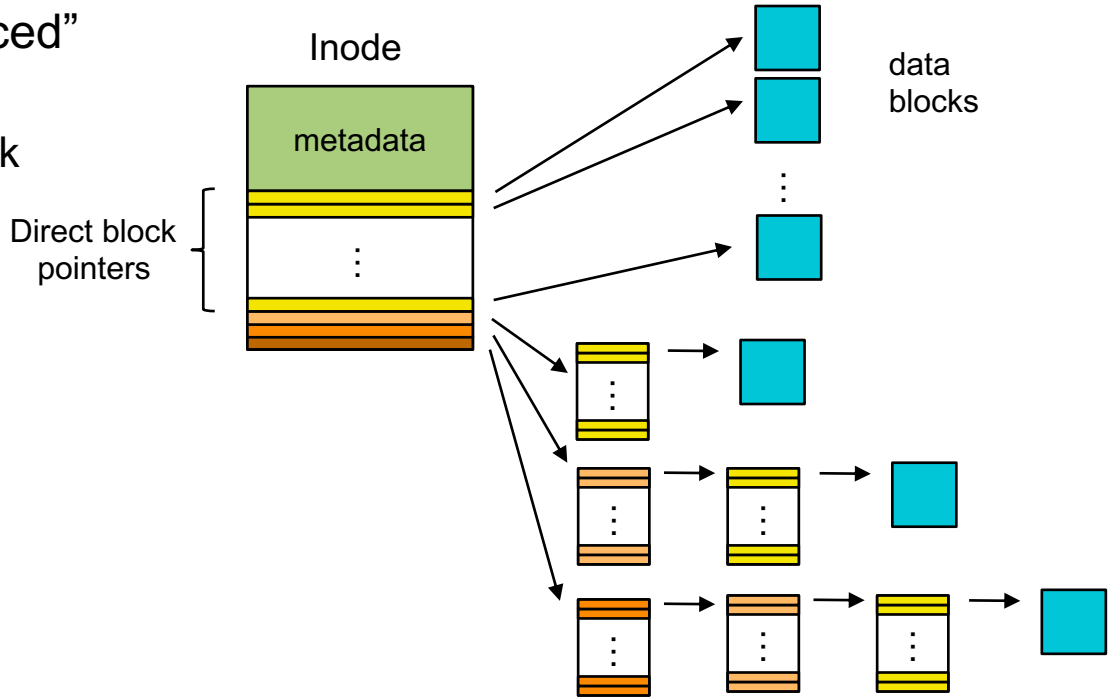
Viewing Metadata

- `ls -l` reads metadata from the inode, using the `stat` syscall



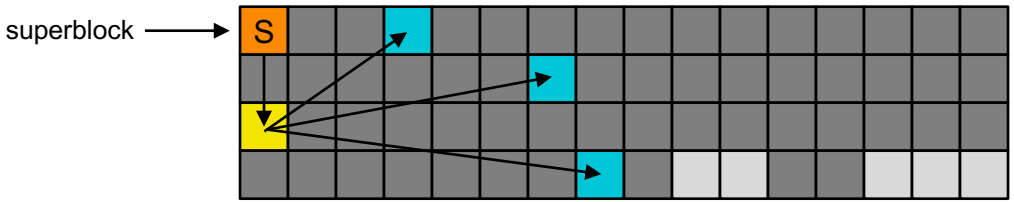
Unix Inodes and Indirect Blocks

- Unix inodes use an “unbalanced” indexed structure
  - Each inode contains ~15 block pointers
  - First 12 are direct blocks
  - 1 single indirect block
  - 1 double indirect block
  - 1 triple indirect block
- Inodes are small
  - 256 bytes each



Superblock

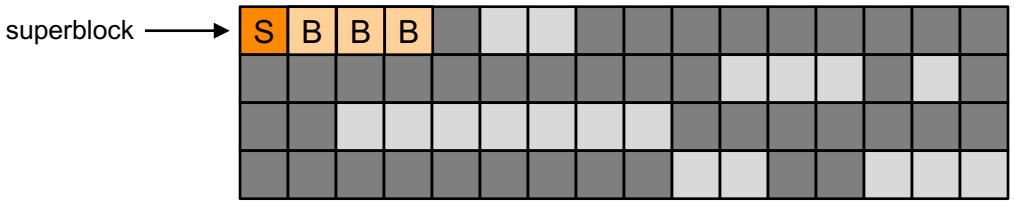
- "/" is the directory that is the root of the file system
- How do we find the inode for "/"?



- The superblock S stores a pointer to the inode of "/"
  - The inode for "/" has pointers to all of the blocks storing the directory entries for "/"
- It is the basis for translating all path names
- It is at a fixed, pre-determined location on disk

Block Allocation

- File system needs to keep track of which blocks have been allocated and which are free

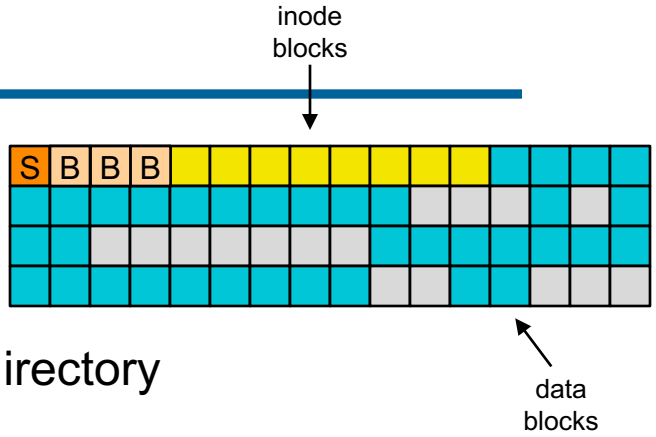


- Free map blocks B store a bitmap, one bit per block
  - A set bit indicates that the block is allocated
  - One bitmap for data blocks
  - Another for inode blocks

Block Allocation - Tradeoffs

- Bitmap
  - Pro: easy to find contiguous blocks
  - Con: need extra space to store the bitmap
- Linked list
  - Pro: no wasted space for bitmap
    - » Use free blocks themselves to store free block list
  - Con: harder to find contiguous blocks

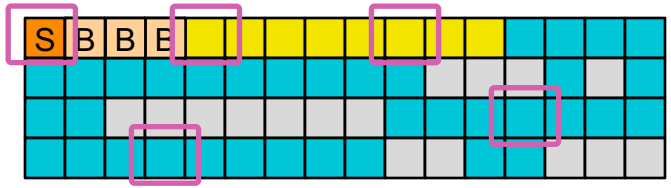
File System Layout



- How do file systems use the disk to store files?
- File systems define a block size (e.g., 4KB)
  - Allocate disk space in the granularity of blocks
- A superblock determines the location of the root directory
  - Always at a well-known disk location
- A free map determines which blocks are free and allocated
  - Usually a bitmap, one bit per block on the disk
- Inodes store metadata about files and the locations of their blocks
- Remaining disk blocks used to store files and directories
  - There are many ways to do this

Revisiting Path Name Translation

- Suppose you want to open “/one”
- What does the file system do?
  - To open “/one”, use superblock to find inode for “/”
  - Read inode for “/” into memory
  - Open and read “/” directory, look for entry “one”
  - This entry specifies the inode number
  - Read the inode for “one” into memory
  - The inode says where the first data block is on disk
  - Read that block into memory to access the data in the file

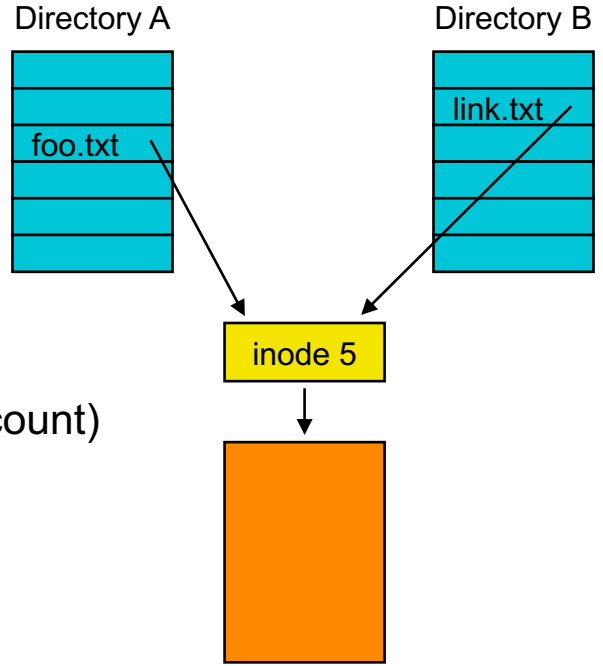


Today's Outline

- File system layout
  - Managing disk space
  - Metadata
  - Path name translation
- Common file operations
  - Hard links
  - Symbolic (soft) links
  - Create
  - Rename
  - Delete

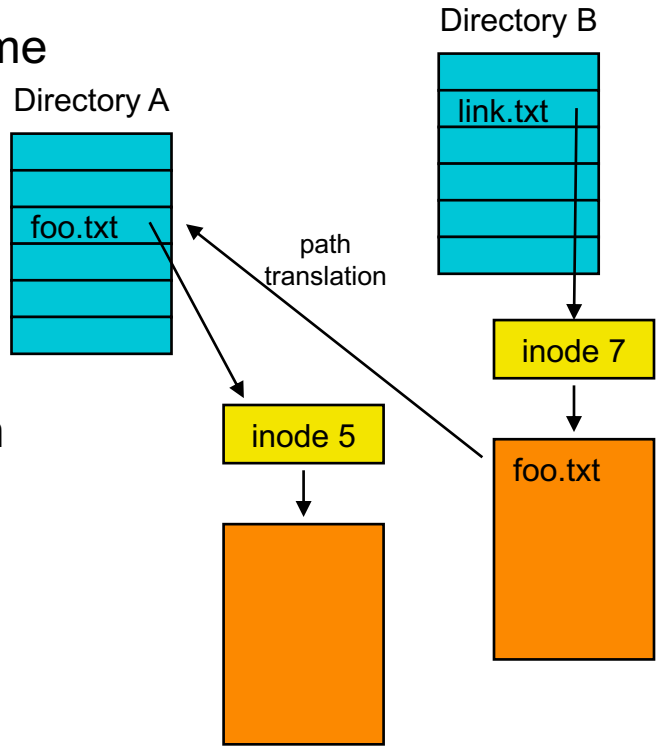
Hard Links

- Hard link: a directory entry that associates a name with a file
- Enables a form of aliasing:
  - `> ln file alias`
  - Uses `link` syscall
  - Alias points to the same inode
- "." and ".." names are hard links to directories
- Deleting a link may or may not remove the file
  - Depends on whether it's the last link (use reference count)
- Limitations:
  - Users cannot create hard links to directories
  - Cannot create hard links to files in other file systems



Symbolic (Soft) Links

- Soft link: a file whose contents are another file name
  - File contains the file name
  - Inode is flagged as a soft link
- Enables another form of aliasing:
  - `> ln -s file alias`
  - Uses `symlink` syscall
- Soft link creates an alias via path name translation
  - File system reads the path alias from the file
  - File system restarts translation
- Limitations:
  - Slower than hard links



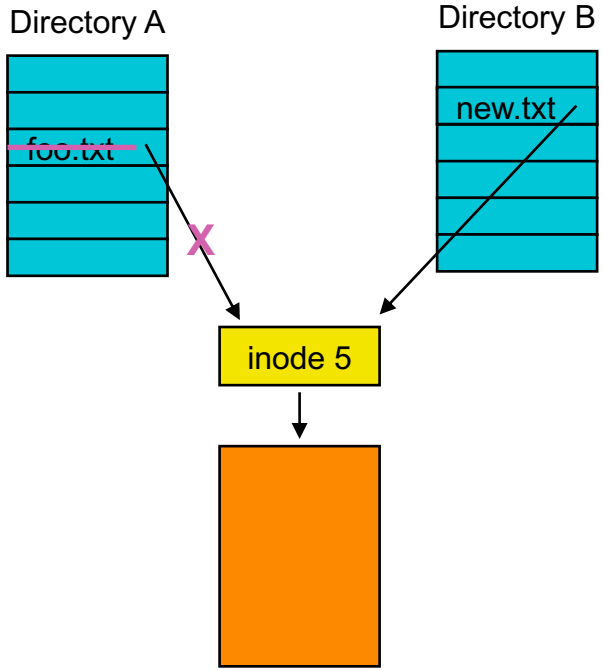
(Live Demo of Links)

Create

- Creating a file “new.txt” is pretty straightforward
- Allocate an inode
  - Initialize the metadata (owner, protection, timestamp, etc.)
  - Update inode bitmap
- Allocate a directory entry
  - Entry maps “new.txt” to the allocated inode
- When process starts writing, allocate data blocks
  - Update inode to point to allocated data blocks
  - Update data block bitmap
  - Continue to allocate blocks on demand

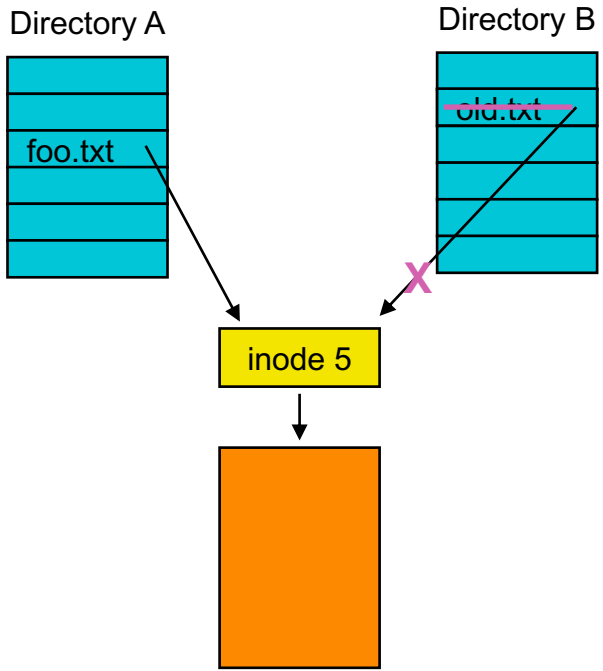
Rename

- One approach: create a new file with the new name, copy contents, delete old file
- More efficient approach:
  - Create a new directory entry with the new name
  - Point to the existing inode
  - Delete the directory entry with the old name
- Execute with mv:
  - `> mv old new`
  - Uses `rename` syscall



Delete

- Steps for deleting a file “old.txt”:
  - Remove the directory entry for “old.txt”
    - » Hence the syscall name unlink
  - Decrement the reference count in the inode
  - If the file still has links to it, that’s all
  - If there are no remaining links:
    - » Free up the data blocks (update the data block bitmap)
    - » Free up the inode (update the inode bitmap)
    - » Block data is not erased
- If the file is still open in any process, the directory entry is removed but the file blocks are not



File System Layout Summary

- File system layout
  - Multi-level indexed layouts
  - Inodes
  - Superblocks and bitmaps
  - Path name translation
- Common file operations
  - Hard links
  - Symbolic (soft) links
  - Create
  - Rename
  - Delete

For next class…

- Read chapters 41 and 42