File Systems, Naming, and Directories

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Goals for Today

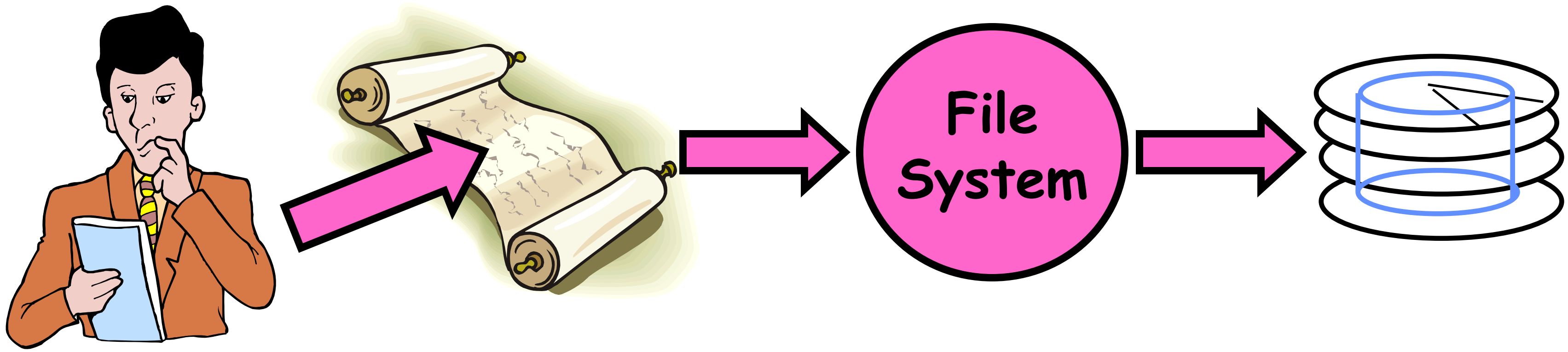
- File Systems
  - Structure, Naming, Directories

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from my lecture notes by Kubiatowicz.

Building a File System

- **File System:** Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.
- File System Components
  - Disk Management: collecting disk blocks into files
  - Naming: Interface to find files by name, not by blocks
  - Protection: Layers to keep data secure
  - Reliability/Durability: Keeping of files durable despite crashes, media failures, attacks, etc
- User vs. System View of a File
  - User's view:
    - » Durable Data Structures
  - System's view (system call interface):
    - » Collection of Bytes (UNIX)
    - » Doesn't matter to system what kind of data structures you want to store on disk!
  - System's view (inside OS):
    - » Collection of blocks (a block is a logical transfer unit, while a sector is the physical transfer unit)
    - » Block size $\geq$ sector size; in UNIX, block size is 4KB

Translating from User to System View



- What happens if user says: *give me bytes 2—12?*
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about: write bytes 2—12?
  - Fetch block
  - Modify portion
  - Write out Block
- Everything inside File System is in whole size blocks
  - For example, `getc()`, `putc()` ⇒ buffers something like 4096 bytes, even if interface is one byte at a time
- From now on, file is a collection of blocks

Disk Management Policies

- Basic entities on a disk:
  - File: user-visible group of blocks arranged sequentially in logical space
  - Directory: user-visible index mapping names to files (next lecture)
- Access disk as linear array of sectors. Two Options:
  - Identify sectors as vectors [cylinder, surface, sector]. Sort in cylinder-major order. Not used much anymore.
  - Logical Block Addressing (LBA). Every sector has integer address from zero up to max number of sectors.
  - Controller translates from address ⇒ physical position
    - » First case: OS/BIOS must deal with bad sectors
    - » Second case: hardware shields OS from structure of disk
- Need way to track free disk blocks
  - Link free blocks together ⇒ too slow today
  - Use bitmap to represent free space on disk
- Need way to structure files: File Header
  - Track which blocks belong at which offsets within the logical file structure
  - Optimize placement of files' disk blocks to match access and usage patterns

Designing the File System: Access Patterns

- How do users access files?
  - Need to know type of access patterns user is likely to throw at system
- Sequential Access: bytes read in order ("give me the next X bytes, then give me next, etc")
  - Almost all file access are of this flavor
- Random Access: read/write element out of middle of array ("give me bytes i—j")
  - Less frequent, but still important. For example, virtual memory backing file: page of memory stored in file
  - Want this to be fast – don't want to have to read all bytes to get to the middle of the file
- Content-based Access: ("find me 100 bytes starting with KUBIATOWICZ")
  - Example: employee records – once you find the bytes, increase my salary by a factor of 2
  - Many systems don't provide this; instead, databases are built on top of disk access to index content (requires efficient random access)

Designing the File System: Usage Patterns

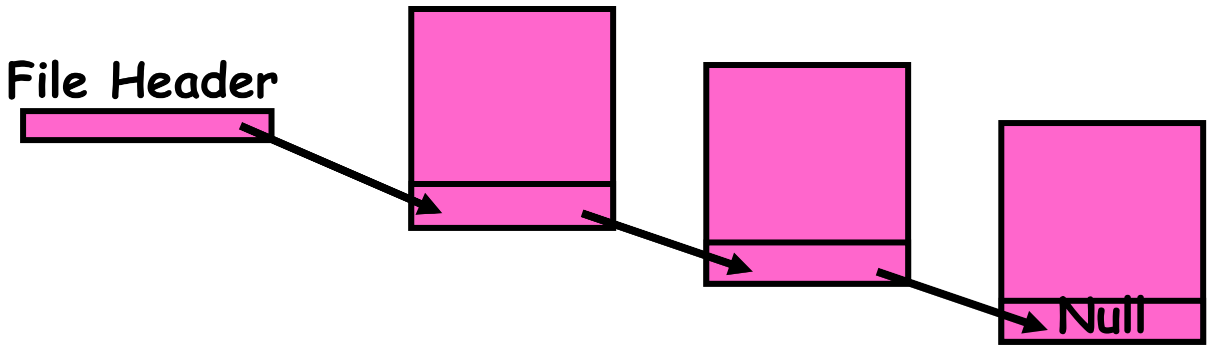
- Most files are small (for example, .login, .c files)
  - A few files are big – nachos, core files, etc.; the nachos executable is as big as all of your .class files combined
  - However, most files are small – .class's, .o's, .c's, etc.
- Large files use up most of the disk space and bandwidth to/from disk
  - May seem contradictory, but a few enormous files are equivalent to an immense # of small files
- Although we will use these observations, beware usage patterns:
  - Good idea to look at usage patterns: beat competitors by optimizing for frequent patterns
  - Except: changes in performance or cost can alter usage patterns. Maybe UNIX has lots of small files because big files are really inefficient?

How to organize files on disk

- Goals:
  - Maximize sequential performance
  - Easy random access to file
  - Easy management of file (growth, truncation, etc)
- First Technique: Continuous Allocation
  - Use continuous range of blocks in logical block space
    - » Analogous to base+bounds in virtual memory
    - » User says in advance how big file will be (disadvantage)
  - Search bit-map for space using best fit/first fit
    - » What if not enough contiguous space for new file?
  - File Header Contains:
    - » First sector/LBA in file
    - » File size (# of sectors)
  - Pros: Fast Sequential Access, Easy Random access
  - Cons: External Fragmentation/Hard to grow files
    - » Free holes get smaller and smaller
    - » Could compact space, but that would be *really* expensive
- Continuous Allocation used by IBM 360
  - Result of allocation and management cost: People would create a big file, put their file in the middle

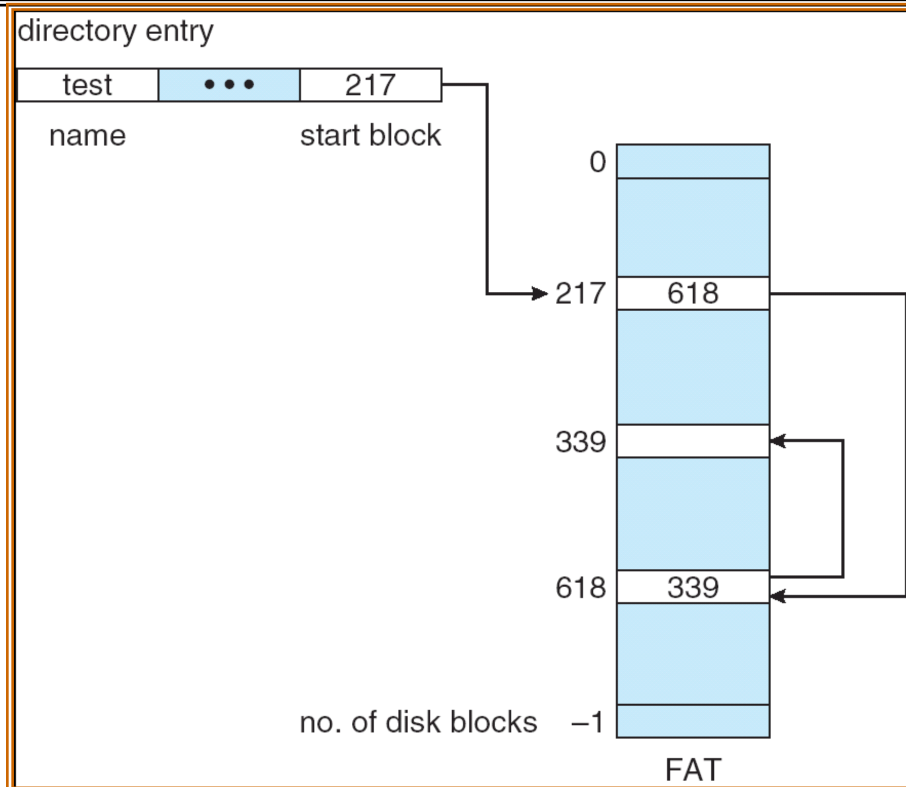
Linked List Allocation

- Second Technique: Linked List Approach
  - Each block, pointer to next on disk



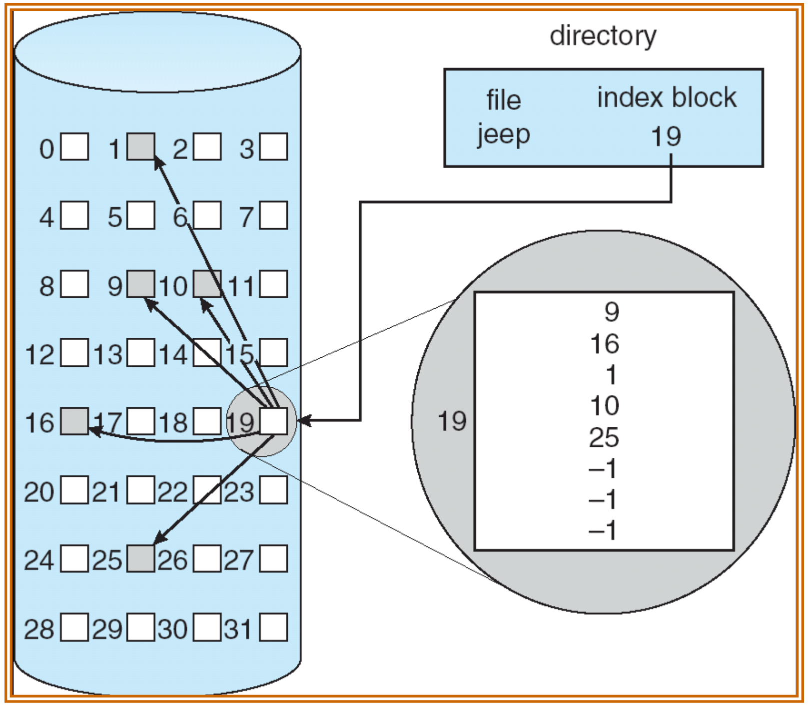
  - Pros: Can grow files dynamically, Free list same as file
  - Cons: Bad Sequential Access (seek between each block), Unreliable (lose block, lose rest of file)
  - Serious Con: Bad random access!!!!
  - Technique originally from Alto (First PC, built at Xerox)
    - » No attempt to allocate contiguous blocks

Linked Allocation: File-Allocation Table (FAT)



- MSDOS links pages together to create a file
  - Links not in pages, but in the File Allocation Table (FAT)
    - » FAT contains an entry for each block on the disk
    - » FAT Entries corresponding to blocks of file linked together
  - Access properies:
    - » Sequential access expensive unless FAT cached in memory
    - » Random access expensive always, but *really* expensive if FAT not cached in memory

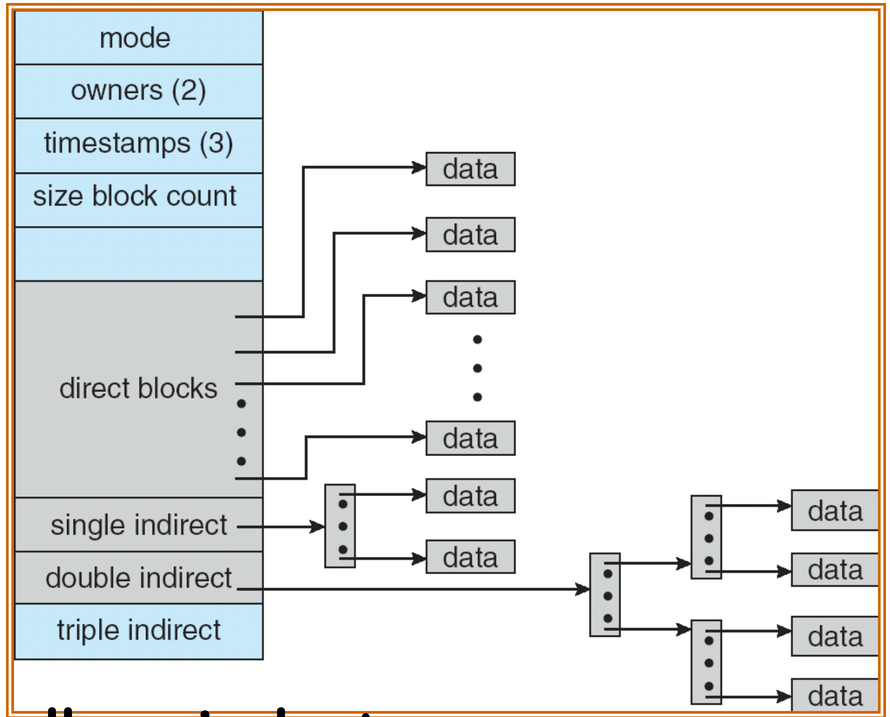
Indexed Allocation



- Indexed Files (Nachos, VMS)
  - System Allocates file header block to hold array of pointers big enough to point to all blocks
    - » User pre-declares max file size;
  - Pros: Can easily grow up to space allocated for index
    Random access is fast
  - Cons: Clumsy to grow file bigger than table size
    Still lots of seeks: blocks may be spread over disk

Multilevel Indexed Files (UNIX 4.1)

- Multilevel Indexed Files: Like multilevel address translation (from UNIX 4.1 BSD)
  - Key idea: efficient for small files, but still allow big files



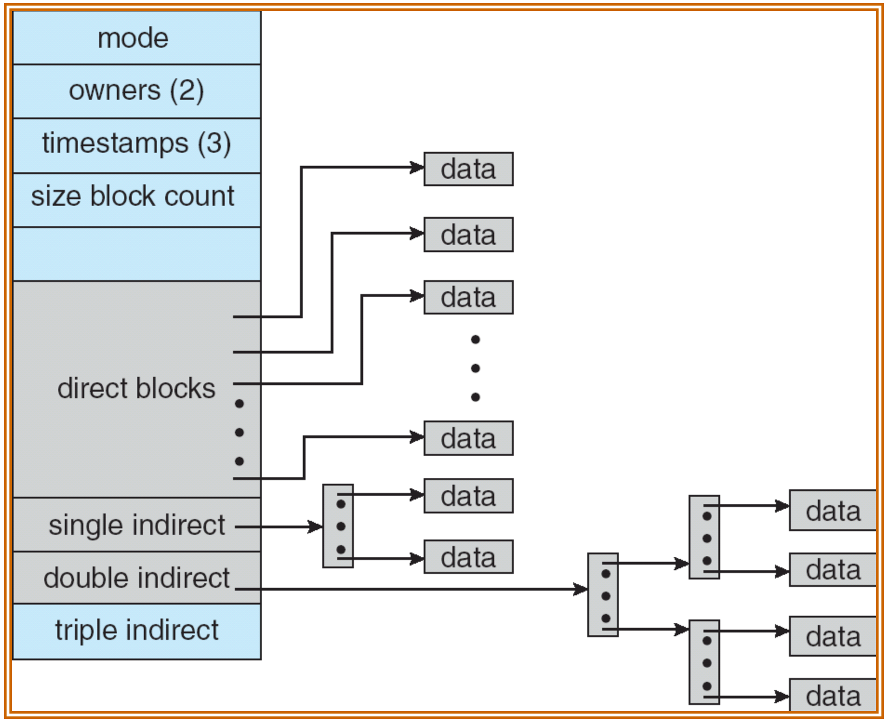
- File hdr contains 13 pointers
  - Fixed size table, pointers not all equivalent
  - This header is called an "inode" in UNIX
- File Header format:
  - First 10 pointers are to data blocks
  - Ptr 11 points to "indirect block" containing 256 block ptrs
  - Pointer 12 points to "doubly indirect block" containing 256 indirect block ptrs for total of 64K blocks
  - Pointer 13 points to a triply indirect block (16M blocks)

Multilevel Indexed Files (UNIX 4.1): Discussion

- Basic technique places an upper limit on file size that is approximately 16Gbytes
  - Designers thought this was bigger than anything anyone would need. Much bigger than a disk at the time…
  - Fallacy: today, EOS producing 2TB of data per day

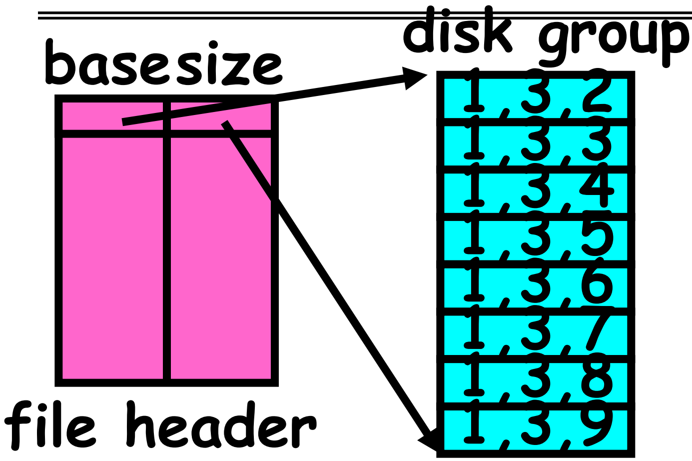
- Pointers get filled in dynamically: need to allocate indirect block only when file grows > 10 blocks
  - On small files, no indirection needed

Example of Multilevel Indexed Files



- Sample file in multilevel indexed format:
  - How many accesses for block #23? (assume file header accessed on open)?
    - » Two: One for indirect block, one for data
  - How about block #5?
    - » One: One for data
  - Block #340?
    - » Three: double indirect block, indirect block, and data
- UNIX 4.1 Pros and cons
  - Pros: Simple (more or less)
    Files can easily expand (up to a point)
    Small files particularly cheap and easy
  - Cons: Lots of seeks
    Very large files must read many indirect blocks (four I/Os per block!)

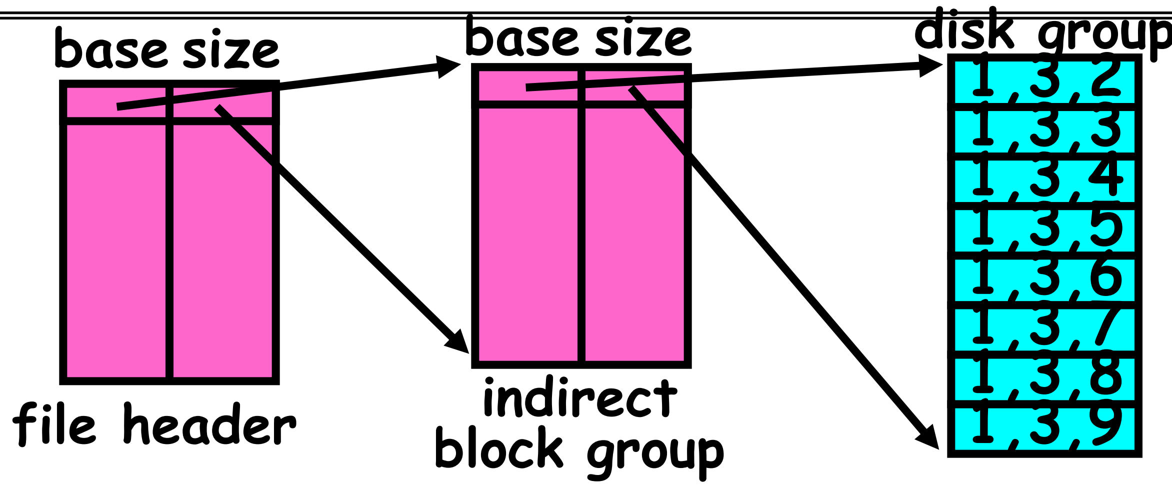
File Allocation for Cray-1 DEMOS



Basic Segmentation Structure:
Each segment contiguous on disk

- DEMOS: File system structure similar to segmentation
  - Idea: reduce disk seeks by
    - » using contiguous allocation in normal case
    - » but allow flexibility to have non-contiguous allocation
  - Cray-1 had 12ns cycle time, so CPU:disk speed ratio about the same as today (a few million instructions per seek)
- Header: table of base & size (10 "block group" pointers)
  - Each block chunk is a contiguous group of disk blocks
  - Sequential reads within a block chunk can proceed at high speed – similar to continuous allocation
- How do you find an available block group?
  - Use freelist bitmap to find block of 0's.

Large File Version of DEMOS



- What if need much bigger files?
  - If need more than 10 groups, set flag in header: BIGFILE
    - » Each table entry now points to an indirect block group
  - Suppose 1000 blocks in a block group ⇒ 80GB max file
    - » Assuming 8KB blocks, 8byte entries⇒
      (10 ptrs×1024 groups/ptr×1000 blocks/group)*8K =80GB
- Discussion of DEMOS scheme
  - Pros: Fast sequential access, Free areas merge simply
    Easy to find free block groups (when disk not full)
  - Cons: Disk full ⇒ No long runs of blocks (fragmentation),
    so high overhead allocation/access
  - Full disk ⇒ worst of 4.1BSD (lots of seeks) with worst of continuous allocation (lots of recompaction needed)

How to keep DEMOS performing well?

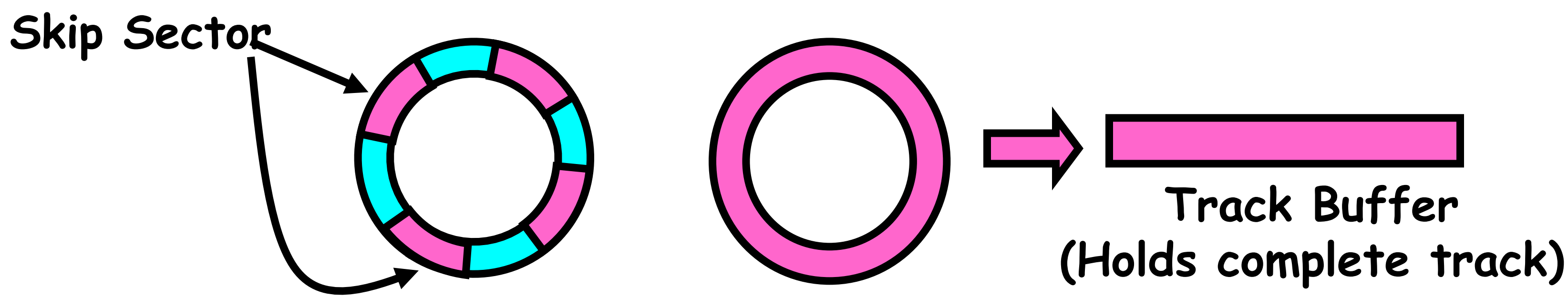
- In many systems, disks are always full
  - CS department growth: 300 GB to 1TB in a year
    - » That's 2GB/day! (Now at 6 TB?)
  - How to fix? Announce that disk space is getting low, so please delete files?
    - » Don't really work: people try to store their data faster
  - Sidebar: Perhaps we are getting out of this mode with new disks… However, let's assume disks full for now
    - » (Rumor has it that the EECS department has 60TB of spinning storage just waiting for use…)
- Solution:
  - Don't let disks get completely full: reserve portion
    - » Free count = # blocks free in bitmap
    - » Scheme: Don't allocate data if count < reserve
  - How much reserve do you need?
    - » In practice, 10% seems like enough
  - Tradeoff: pay for more disk, get contiguous allocation
    - » Since seeks so expensive for performance, this is a very good tradeoff

UNIX BSD 4.2

- Same as BSD 4.1 (same file header and triply indirect blocks), except incorporated ideas from DEMOS:
  - Uses bitmap allocation in place of freelist
  - Attempt to allocate files contiguously
  - 10% reserved disk space
  - Skip-sector positioning (mentioned next slide)
- Problem: When create a file, don't know how big it will become (in UNIX, most writes are by appending)
  - How much contiguous space do you allocate for a file?
  - In Demos, power of 2 growth: once it grows past 1MB, allocate 2MB, etc
  - In BSD 4.2, just find some range of free blocks
    - » Put each new file at the front of different range
    - » To expand a file, you first try successive blocks in bitmap, then choose new range of blocks
  - Also in BSD 4.2: store files from same directory near each other
- Fast File System (FFS)
  - Allocation and placement policies for BSD 4.2

Attack of the Rotational Delay

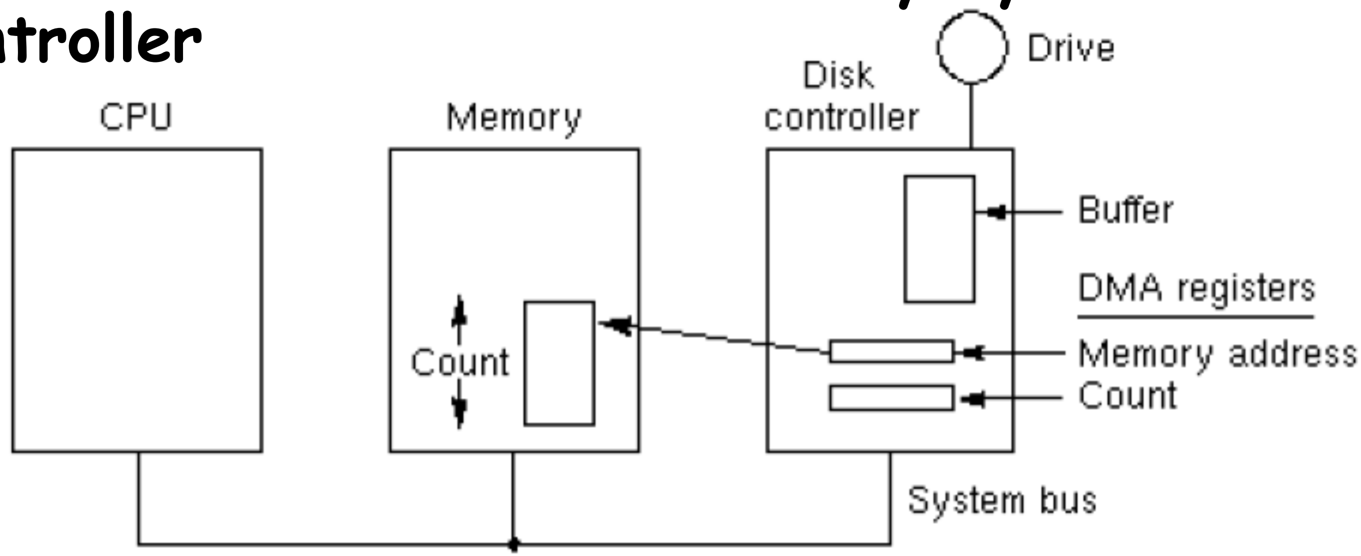
- Problem 2: Missing blocks due to rotational delay
  - Issue: Read one block, do processing, and read next block. In meantime, disk has continued turning: missed next block! Need 1 revolution/block!



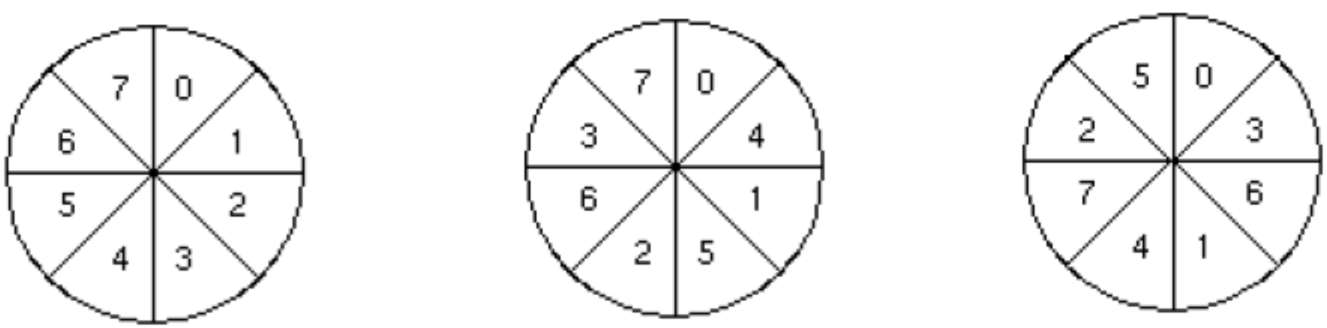
  - Solution1: Skip sector positioning ("interleaving")
    - » Place the blocks from one file on every other block of a track: give time for processing to overlap rotation
  - Solution2: Read ahead: read next block right after first, even if application hasn't asked for it yet.
    - » This can be done either by OS (read ahead)
    - » By disk itself (track buffers). Many disk controllers have internal RAM that allows them to read a complete track
- Important Aside: Modern disks+controllers do many complex things "under the covers"
  - Track buffers, elevator algorithms, bad block filtering

DMA & Interleaving

- A DMA transfer is done entirely by the controller



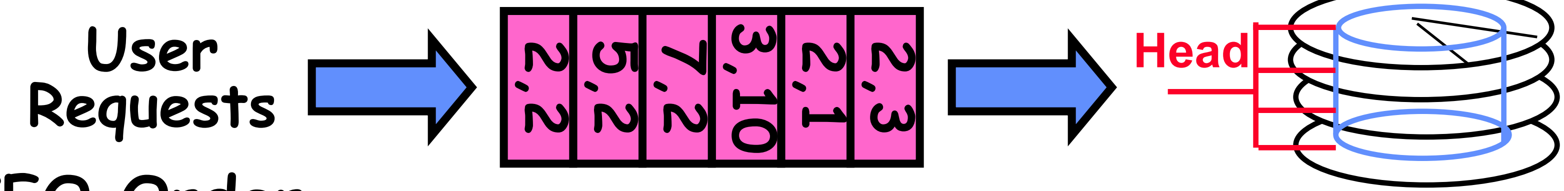
- Interleaving



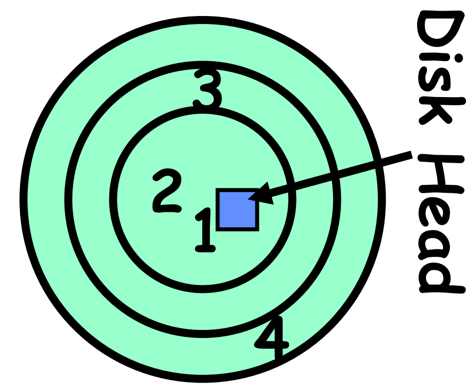
No interleaving Single interleaving Double interleaving

Disk Scheduling

- Disk can do only one request at a time; What order do you choose to do queued requests?



- FIFO Order
  - Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  - Pick the request that's closest on the disk
  - Although called SSTF, today must include rotational delay in calculation, since rotation can be as long as seek
  - Con: SSTF good at reducing seeks, but may lead to starvation



- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  - No starvation, but retains flavor of SSTF
- C-SCAN: Circular-Scan: only goes in one direction
  - Skips any requests on the way back
  - Fairer than SCAN, not biased towards pages in middle

Example of Disk Scheduling

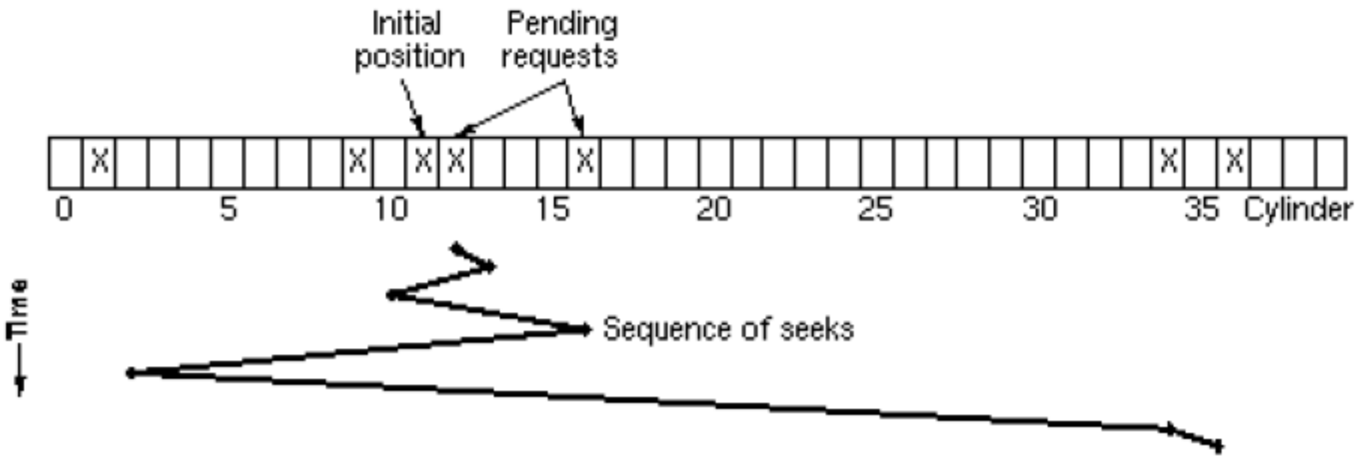
- 40 cylinders
- While the seek to cylinder 11 is in progress
- 1, 36, 16, 34, 9, 12 are requested in that order

- FIFO
  - 10+35+20+18+25+3=111 arm motions

Example of Disk Scheduling(2)

- 40 cylinders
- While the seek to cylinder 11 is in progress
- 1, 36, 16, 34, 9, 12 are requested in that order

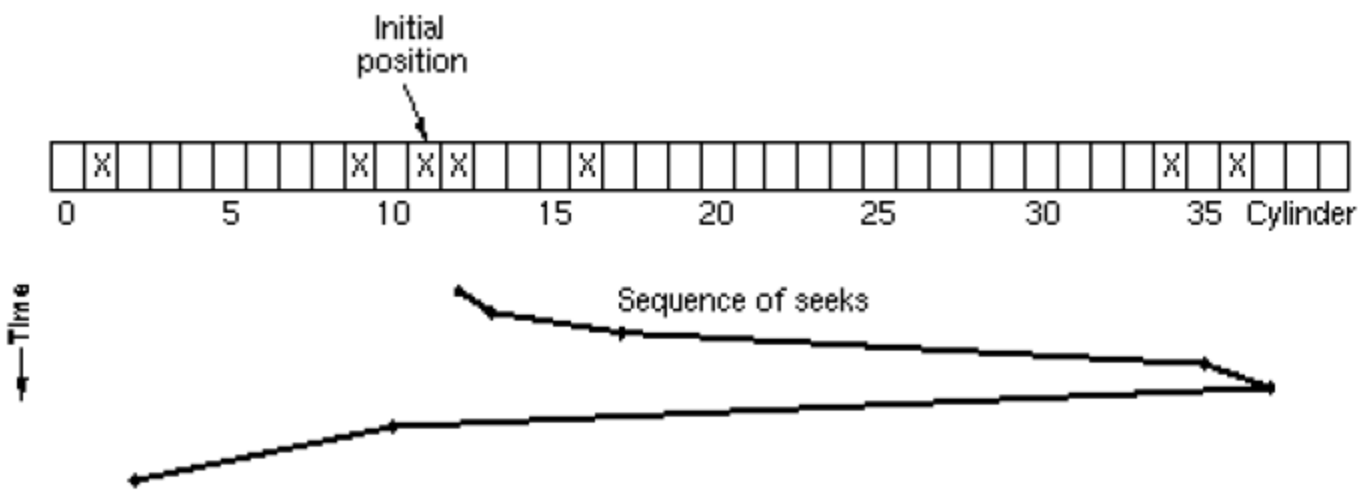
- SSTF(Shortest Seek Time First)
  - 1+3+7+15+33+2=61 arm motions



Example of Disk Scheduling(3)

- 40 cylinders
- While the seek to cylinder 11 is in progress
- 1, 36, 16, 34, 9, 12 are requested in that order

- SCAN – Elevator algorithm
  - 1+4+18+2+27+8=60 arm motions



How do we actually access files?

- All information about a file contained in its file header
  - UNIX calls this an "inode"
    - » Inodes are global resources identified by index ("inumber")
  - Once you load the header structure, all the other blocks of the file are locatable
- Question: how does the user ask for a particular file?
  - One option: user specifies an inode by a number (index).
    - » Imagine: open("14553344")
  - Better option: specify by textual name
    - » Have to map name→inumber
  - Another option: Icon
    - » This is how Apple made its money. Graphical user interfaces. Point to a file and click.
- Naming: The process by which a system translates from user-visible names to system resources
  - In the case of files, need to translate from strings (textual names) or icons to inumbers/inodes
  - For global file systems, data may be spread over globe⇒need to translate from strings or icons to some combination of physical server location and inumber

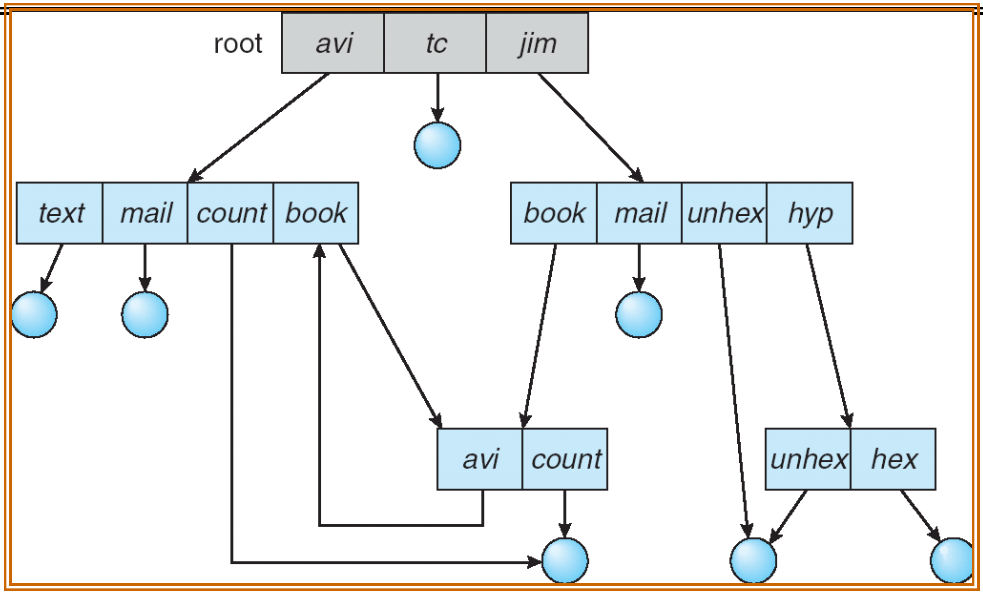
Directories

- **Directory**: a relation used for naming
  - Just a table of (file name, inumber) pairs
- How are directories constructed?
  - Directories often stored in files
    - » Reuse of existing mechanism
    - » Directory named by inode/inumber like other files
  - Needs to be quickly searchable
    - » Options: Simple list or Hashtable
    - » Can be cached into memory in easier form to search
- How are directories modified?
  - Originally, direct read/write of special file
  - System calls for manipulation: `mkdir`, `rmdir`
  - Ties to file creation/destruction
    - » On creating a file by name, new inode grabbed and associated with new file in particular directory

Directory Organization

- Directories organized into a hierarchical structure
  - Seems standard, but in early 70's it wasn't
  - Permits much easier organization of data structures
- Entries in directory can be either files or directories
- Files named by ordered set (e.g., /programs/p/list)

Directory Structure



- Not really a hierarchy!
  - Many systems allow directory structure to be organized as an acyclic graph or even a (potentially) cyclic graph
  - Hard Links: different names for the same file
    - » Multiple directory entries point at the same file
  - Soft Links: "shortcut" pointers to other files
    - » Implemented by storing the logical name of actual file
- **Name Resolution:** The process of converting a logical name into a physical resource (like a file)
  - Traverse succession of directories until reach target file
  - Global file system: May be spread across the network

Directory Structure (Con't)

- How many disk accesses to resolve "/my/book/count"?
  - Read in file header for root (fixed spot on disk)
  - Read in first data block for root
    - » Table of file name/index pairs. Search linearly – ok since directories typically very small
  - Read in file header for "my"
  - Read in first data block for "my"; search for "book"
  - Read in file header for "book"
  - Read in first data block for "book"; search for "count"
  - Read in file header for "count"
- **Current working directory:** Per-address-space pointer to a directory (inode) used for resolving file names
  - Allows user to specify relative filename instead of absolute path (say CWD="/my/book" can resolve "count")

Summary

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for access and usage patterns
  - Maximize sequential access, allow efficient random access
- File (and directory) defined by header
  - Called "inode" with index called "inumber"
- Multilevel Indexed Scheme
  - Inode contains file info, direct pointers to blocks,
  - indirect blocks, doubly indirect, etc..

Summary(2)

- Cray DEMOS: optimization for sequential access
  - Emphersized contiguous allocation of blocks, but allowed to use non-contiguous allocation when necessary

- 4.2 BSD Multilevel index files
  - Inode contains pointers to actual blocks, indirect blocks, double indirect blocks, etc
  - Optimizations for sequential access: start new files in open ranges of free blocks
  - Rotational Optimization

- Naming: the process of turning user-visible names into resources (such as files)