CS162 Operating Systems and Systems Programming Lecture 14

File Systems (cont'd), Key Value Storage Systems

October 17, 2012

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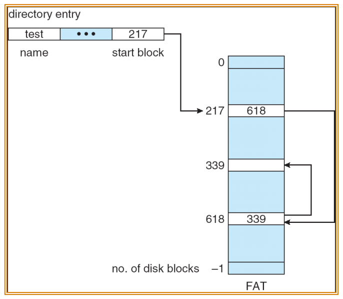
Recap: File System Goals

- Maximize sequential performance
- Efiicient random access to file
- Easy management of files (growth, truncation, etc)

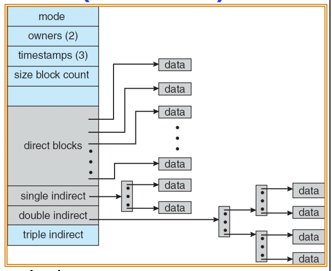
Recap: Linked Allocation



- 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 properties:
    - » Sequential access expensive unless FAT cached in memory
    - » Random *really* expensive if FAT not cached

Multilevel Indexed Files (UNIX 4.1)

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

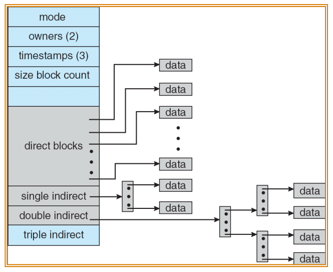


- File hdr contains 13 pointers
  - Fixed size table, pointers not all equivalent
  - This header is called an "inode" in UNIX
- File Header format:
  - First 10 pointers are to data blocks
  - Ptr 11 points to "indirect block" containing 256 block ptrs
  - Pointer 12 points to "doubly indirect block" 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, Facebook gets hundreds of TBs of logs every 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/O's per block!)

UNIX BSD 4.2

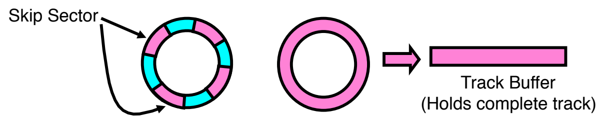
- Same as BSD 4.1 (same file header and triply indirect blocks), except incorporated ideas from Cray-1 DEMOS:
  - Uses bitmap allocation in place of freelist
  - Attempt to allocate files contiguously
  - 10% reserved disk space (mentioned next slide)
  - Skip-sector positioning (mentioned in two slides)
- 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 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

How to Deal with Full Disks?

- In many systems, disks are always full
  - EECS department growth: 300 GB to 1TB in a year (now 10s TB)
  - How to fix? Announce disk space is 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 are full for now
- 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

Attack of the Rotational Delay

- Problem: 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!



  - Solution 1: Skip sector positioning ("interleaving")
    - » Place the blocks from one file on every other block of a track: give time for processing to overlap rotation
  - Solution 2: 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

Quiz 14.1: File Systems

- Q1: True _ False _ With FAT, pointers are maintained in the data blocks
- Q2: True _ False _ Unix file system is more efficient than FAT for random access
- Q3: True _ False _ The "Skip Sector Positioning" technique allows reading consecutive blocks on a track
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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 blocks of 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

- Naming (name resolution): 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

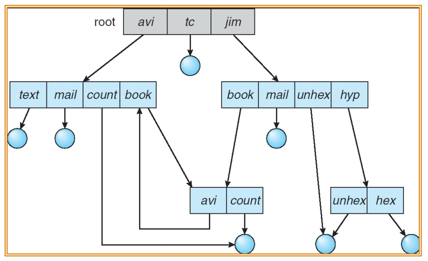
Directories

- 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

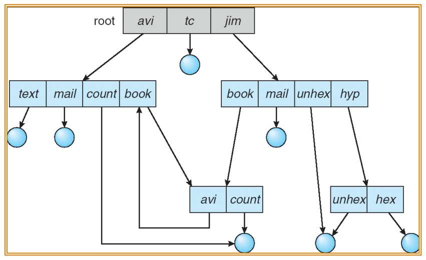
- Directories organized into a hierarchical structure
  - Seems standard, but in early 70's it wasn't
  - Permits much easier organization of data structures
- Entries in directory can be either files or directories
- Files named by ordered set (e.g., `/programs/p/list`)

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

Directory Structure



- 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")

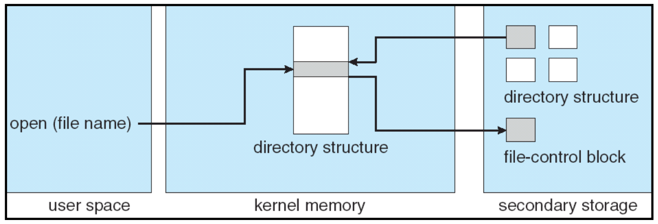
Where are inodes stored?

- In early UNIX and DOS/Windows' FAT file system, headers stored in special array in outermost cylinders
  – Header not stored anywhere near the data blocks. To read a small file, seek to get header, seek back to data.
  – Fixed size, set when disk is formatted. At formatting time, a fixed number of inodes were created (They were each given a unique number, called an "inumber")

Where are inodes stored?

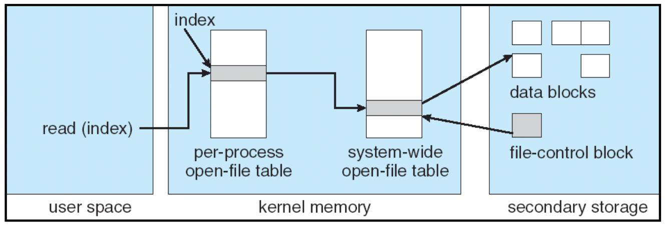
- Later versions of UNIX moved the header information to be closer to the data blocks
  – Often, inode for file stored in same "cylinder group" as parent directory of the file (makes an `ls` of that directory run fast).
  – Pros:
    » UNIX BSD 4.2 puts a portion of the file header array on each cylinder. For small directories, can fit all data, file headers, etc. in same cylinder ⇒ no seeks!
    » File headers much smaller than whole block (a few hundred bytes), so multiple headers fetched from disk at same time
    » Reliability: whatever happens to the disk, you can find many of the files (even if directories disconnected)
  – Part of the Fast File System (FFS)
    » General optimization to avoid seeks

In-Memory File System Structures



- Open system call:
  - Resolves file name, finds file control block (inode)
  - Makes entries in per-process and system-wide tables
  - Returns index (called "file handle") in open-file table

In-Memory File System Structures



- Read/write system calls:
  - Use file handle to locate inode
  - Perform appropriate reads or writes

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File System Summary (1/2)

- 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”
- Multilevel Indexed Scheme
  - Inode contains file info, direct pointers to blocks,
  - indirect blocks, doubly indirect, etc..

File System Summary (2/2)

- 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: act of translating from user-visible names to actual system resources
  - Directories used for naming for local file systems