CS194-24
Advanced Operating Systems Structures and Implementation
Lecture 13

File Systems (Con't)
RAID/Journaling/VFS

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Goals for Today

- File Systems (Continued)
- Durability
  - RAID
  - Log-structured File System, Journaling
- VFS

Interactive is important!

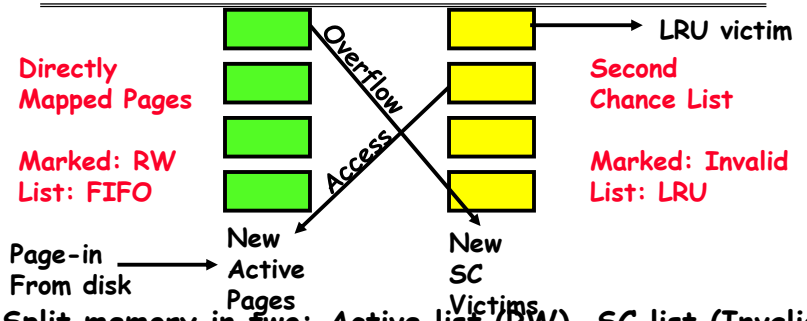
Ask Questions!

Note: Some slides and/or pictures in the following are adapted from slides ©2013

Recall: Implementing LRU

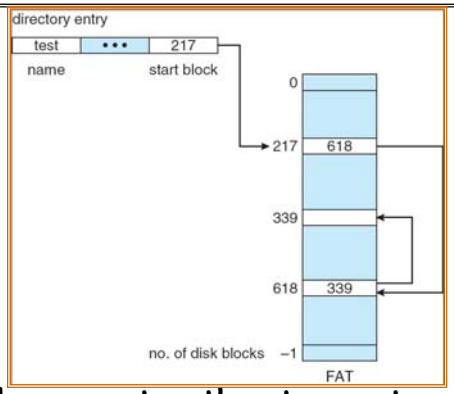
- Perfect:
  - Timestamp page on each reference
  - Keep list of pages ordered by time of reference
  - Too expensive to implement in reality for many reasons
- Clock Algorithm: Arrange physical pages in circle with single clock hand
  - Approximate LRU (approx to approx to MIN)
  - Replace an old page, not the oldest page
- Details:
  - Hardware "use" bit per physical page:
    - » Hardware sets use bit on each reference
    - » If use bit isn't set, means not referenced in a long time
    - » Nachos hardware sets use bit in the TLB; you have to copy this back to page table when TLB entry gets replaced
  - On page fault:
    - » Advance clock hand (not real time)
    - » Check use bit: 1→used recently; clear and leave alone
      0→selected candidate for replacement
  - Will always find a page or loop forever?
    - » Even if all use bits set, will eventually loop around⇒FIFO

Recall: Second-Chance List Algorithm (VAX/VMS)



- Split memory in two: Active list (RW), SC list (Invalid)
- Access pages in Active list at full speed
- Otherwise, Page Fault
  - Always move overflow page from end of Active list to front of Second-chance list (SC) and mark invalid
  - Desired Page On SC List: move to front of Active list, mark RW
  - Not on SC list: page in to front of Active list, mark RW; page out LRU victim at end of SC list

Recall: Linked Allocation: File-Allocation Table (FAT)



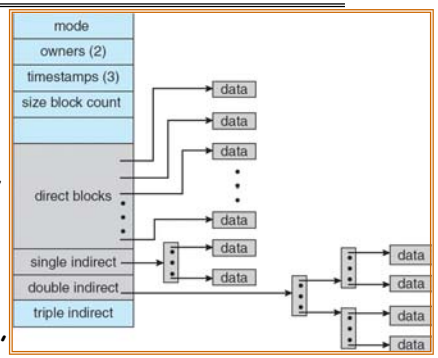
- MSDOS links pages together to create a file
  - Links not in pages, but in the File Allocation Table (FAT)
    - » FAT contains an entry for each block on the disk
    - » FAT Entries corresponding to blocks of file linked together
  - Access properies:
    - » Sequential access expensive unless FAT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

Multilevel Indexed Files (UNIX BSD 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 header 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
    - » Block 11 points to "indirect block" containing 256 blocks
    - » Block 12 points to "doubly indirect block" containing 256 indirect blocks for total of 64K blocks
    - » Block 13 points to a triply indirect block (16M blocks)
- 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

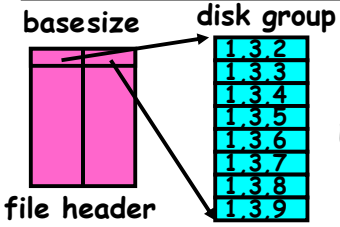


- UNIX 4.1 Pros and cons
  - Pros: Simple (more or less)
    Files can easily expand (up to a point)
    Small files particularly cheap and easy
  - Cons: Lots of seeks
    Very large files must read many indirect block (four I/Os per block!)

Administrivia

- Midterm I: Wednesday (3/12)!
  - Intention is a 1.5 hour exam over 3 hours
  - No class on day of exam!
- Midterm Timing:
  - 7:00-10:00PM in 306 Soda Hall (Here!)
- Topics: everything up to Monday
  - OS Structure, BDD, Process support, Synchronization, Memory Management, File systems
  - Labs/Papers
- Notes: 1 page both sides, hand written

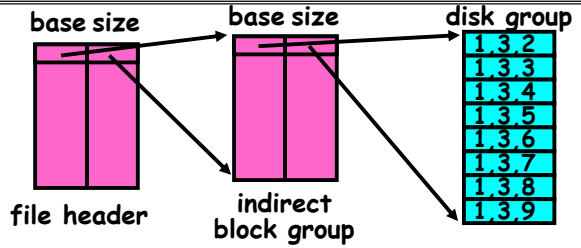
File Allocation for Cray-1 DEMOS



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?

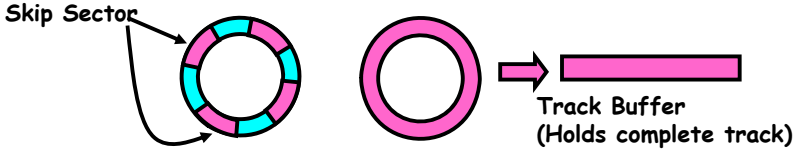
- In many systems, disks are always full
  - How to fix? Announce that disk space is getting low, so please delete files?
    - » Don't really work: people try to store their data faster
  - Sidebar: Perhaps we are getting out of this mode with new disks… However, let's assume disks full for now
- Solution:
  - 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)
- Fast File System (FFS)
  - Allocation and placement policies for BSD 4.2
- 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: store files from same directory near each other
- Problem: Block size (512) too small
  - Increase block size to 4096 or 8192
  - Bitmask to allow files to consume partial fragment

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! 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

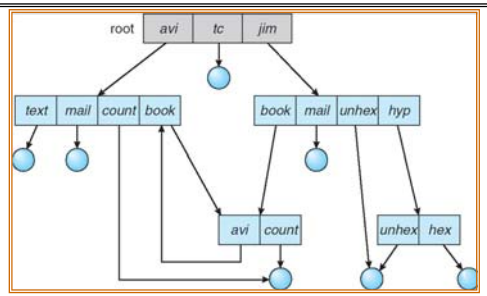
How do we actually access files?

- 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
- Directories organized into a hierarchical structure
  - Entries in directory can be either files or directories
  - Files named by "path" through directory structure: e.g. /usr/homes/george/data.txt

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")

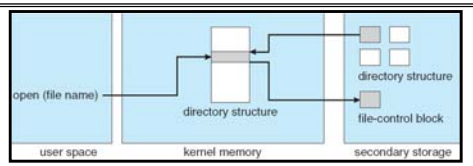
Where are inodes stored?

- In early UNIX and DOS/Windows' FAT file system, headers stored in special array in outermost cylinders
  - Header not stored 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")

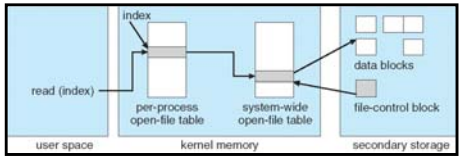
Where are inodes stored?

- 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



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

File System Caching

- Key Idea: Exploit locality by caching data in memory
  - Name translations: Mapping from paths→inodes
  - Disk blocks: Mapping from block address→disk content
- **Buffer Cache:** Memory used to cache kernel resources, including disk blocks and name translations
  - Can contain "dirty" blocks (blocks yet on disk)
- Replacement policy? LRU
  - Can afford overhead of timestamps for each disk block
  - Advantages:
    - » Works very well for name translation
    - » Works well in general as long as memory is big enough to accommodate a host's working set of files.
  - Disadvantages:
    - » Fails when some application scans through file system, thereby flushing the cache with data used only once
    - » Example: `find . -exec grep foo {} \;`
- Other Replacement Policies?
  - Some systems allow applications to request other policies
  - Example, 'Use Once':
    - » File system can discard blocks as soon as they are used

File System Caching (con't)

- Cache Size: How much memory should the OS allocate to the buffer cache vs virtual memory?
  - Too much memory to the file system cache ⇒ won't be able to run many applications at once
  - Too little memory to file system cache ⇒ many applications may run slowly (disk caching not effective)
  - Solution: adjust boundary dynamically so that the disk access rates for paging and file access are balanced
- **Read Ahead Prefetching:** fetch sequential blocks early
  - Key Idea: exploit fact that most common file access is sequential by prefetching subsequent disk blocks ahead of current read request (if they are not already in memory)
  - Elevator algorithm can efficiently interleave groups of prefetches from concurrent applications
  - How much to prefetch?
    - » Too many imposes delays on requests by other applications
    - » Too few causes many seeks (and rotational delays) among concurrent file requests

File System Caching (con't)

- **Delayed Writes:** Writes to files not immediately sent out to disk
  - Instead, `write()` copies data from user space buffer to kernel buffer (in cache)
    - » Enabled by presence of buffer cache: can leave written file blocks in cache for a while
    - » If some other application tries to read data before written to disk, file system will read from cache
  - Flushed to disk periodically (e.g. in UNIX, every 30 sec)
  - Advantages:
    - » Disk scheduler can efficiently order lots of requests
    - » Disk allocation algorithm can be run with correct size value for a file
    - » Some files need never get written to disk! (e..g temporary scratch files written /tmp often don't exist for 30 sec)
  - Disadvantages
    - » What if system crashes before file has been written out?
    - » Worse yet, what if system crashes before a directory file has been written out? (lose pointer to inode!)

The Linux Page Cache

- Goal: Minimize disk I/O by storing data in memory
  - Caches *any* page-based objects, including files and memory mappings
- Cache consists of many *address_space* objects
  - Really misnamed should be a "page_cache_entity" or "physical_pages_of_a_file"
  - Can hold one or more pages from a file or swapper
  - Often associated with an inode, but doesn't have to be
- Searching an address_space object for given page is done by *offset*
  - Contains a set of address_space operations
    - » For reading/writing pages from disk
  - An address_space contains a radix tree of all pages
- Flusher Threads
  - Start pushing dirty blocks back to disk when free memory shrinks below a specified hreshold

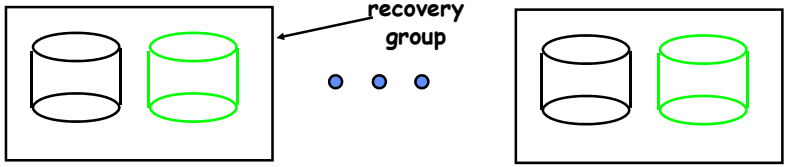
Important "ilities"

- **Availability:** the probability that the system can accept and process requests
  - Often measured in "nines" of probability. So, a 99.9% probability is considered "3-nines of availability"
  - Key idea here is independence of failures
- **Durability:** the ability of a system to recover data despite faults
  - This idea is fault tolerance applied to data
  - Doesn't necessarily imply availability: information on pyramids was very durable, but could not be accessed until discovery of Rosetta Stone
- **Reliability:** the ability of a system or component to perform its required functions under stated conditions for a specified period of time (IEEE definition)
  - Usually stronger than simply availability: means that the system is not only "up", but also working correctly
  - Includes availability, security, fault tolerance/durability
  - Must make sure data survives system crashes, disk crashes, other problems

How to make file system durable?

- Disk blocks contain Reed-Solomon error correcting codes (ECC) to deal with small defects in disk drive
  - Can allow recovery of data from small media defects
- Make sure writes survive in short term
  - Either abandon delayed writes or
  - use special, battery-backed RAM (called non-volatile RAM or NVRAM) for dirty blocks in buffer cache.
- Make sure that data survives in long term
  - Need to replicate! More than one copy of data!
  - Important element: independence of failure
    - » Could put copies on one disk, but if disk head fails…
    - » Could put copies on different disks, but if server fails…
    - » Could put copies on different servers, but if building is struck by lightning….
    - » Could put copies on servers in different continents…
- **RAID:** Redundant Arrays of Inexpensive Disks
  - Data stored on multiple disks (redundancy)
  - Either in software or hardware
    - » In hardware case, done by disk controller; file system may not even know that there is more than one disk in use

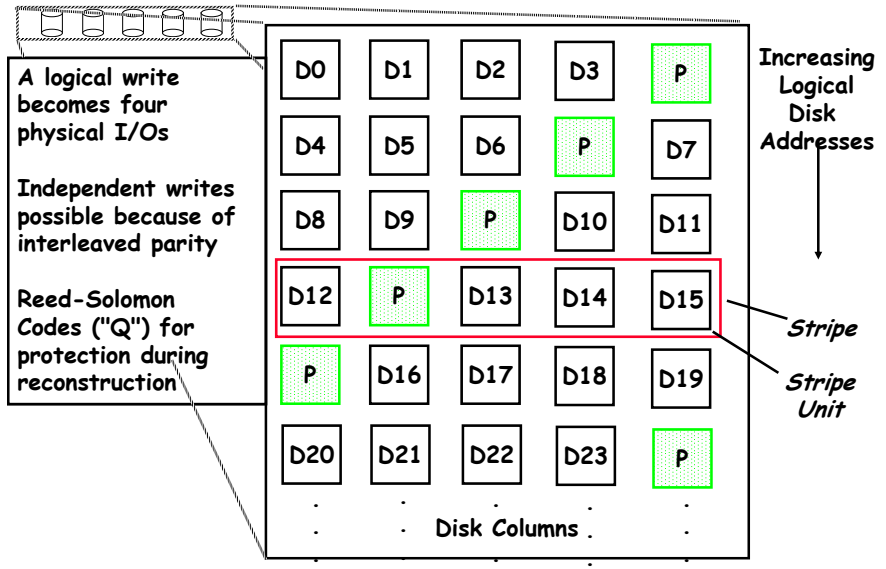
Redundant Arrays of Disks RAID 1: Disk Mirroring/Shadowing



- Each disk is fully duplicated onto its "shadow"
  Very high availability can be achieved
- Bandwidth sacrifice on write:
  Logical write = two physical writes
- Reads may be optimized
- Most expensive solution: 100% capacity overhead

Targeted for high I/O rate , high availability environments

Redundant Arrays of Disks RAID 5+: High I/O Rate Parity



Log Structured and Journaled File Systems

- Better (write) performance through use of log
  - Optimized for writes to disk (log is contiguous)
  - Assume that reads handled through page cache
- Better reliability through use of log
  - All changes are treated as *transactions*
  - A transaction is *committed* once it is written to the log
    - » Data forced to disk for reliability
    - » Process can be accelerated with NVRAM
  - Although File system may not be updated immediately, data preserved in the log
- Difference between "Log Structured" and "Journaled"
  - In a Log Structured filesystem, data stays in log form
  - In a Journaled filesystem, Log used for recovery
- For Journaled system:
  - Log used to asynchronously update filesystem
    - » Log entries removed after used
  - After crash:
    - » Remaining transactions in the log performed ("Redo")
    - » Modifications done in way that can survive crashes
- Examples of Journaled File Systems:
  - Ext3 (Linux), XFS (Unix), etc.

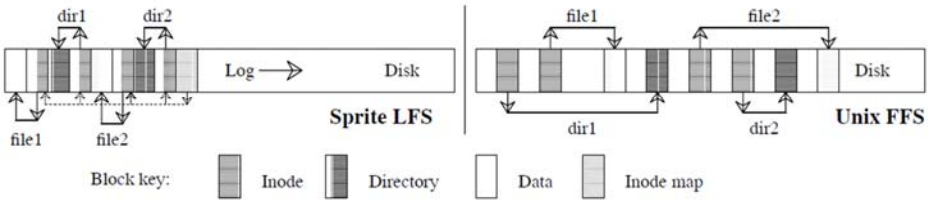
Log-Structured File System – Motivation

- Radically different file system design
- Technology motivations:
  - CPUs outpacing disks: I/O becoming more-and-more of a bottleneck
  - Large RAM: file caches work well, making most disk traffic writes
- Problems with (then) current file systems:
  - Lots of little writes
  - Synchronous: wait for disk in too many places – makes it hard to win much from RAIDs, too little concurrency
  - 5 seeks to create a new file: (rough order)
    1. file i-node (create)
    2. file data
    3. directory entry
    4. file i-node (finalize)
    5. directory i-node (modification time)

LFS Basic Idea

- Log all data and metadata with efficient, large, sequential writes
- Treat the log as the truth, but keep an index on its contents
- Rely on a large memory to provide fast access through caching
- Data layout on disk has "temporal locality" (good for writing), rather than "logical locality" (good for reading)
  - Why is this a better? Because caching helps reads but not writes!
- Two potential problems:
  - Log retrieval on cache misses
  - Wrap-around: what happens when end of disk is reached?
    - » No longer any big, empty runs available
    - » How to prevent fragmentation?

Comparison of LFS and FFS



- Comparison of LFS (Sprite) with FFS (Unix)
  - Creation of two single-block files named dir1/file1 and dir2/file2
  - Each writes new blocks and inodes for file 1 and file 2
  - Each writes new data blocks and inodes for directories
- FFS Traffic:
  - Ten non-sequential writes for new information
  - Inodes each written twice to ease recovery from crashes
- LFS Traffic:
  - Single large write
- For both when reading back: same number of disk accesses

LFS Log Retrieval

- Keep same basic file structure as UNIX (inode, indirect blocks, data)
- Retrieval is just a question of finding a file's inode
- UNIX inodes kept in one or a few big arrays, LFS inodes must float to avoid update-in- place
- Solution: an *inode map* that tells where each inode is (Also keeps other stuff: version number, last access time, free/allocated)
- inode map gets written to log like everything else
- Map of inode map gets written in special checkpoint location on disk; used in crash recovery

LFS Disk Wrap-Around

- Compact live info to open up large runs of free space
  - Problem: long-lived information gets copied over-and-over
- Thread log through free spaces
  - Problem: disk fragments, causing I/O to become inefficient again
- Solution: *segmented log*
  - Divide disk into large, fixed-size segments
  - Do compaction within a segment; thread between segments
  - When writing, use only clean segments (i.e. no live data)
  - Occasionally clean segments: read in several, write out live data in compacted form, leaving some fragments free
  - Try to collect long-lived info into segments that never need to be cleaned
  - Note there is not free list or bit map (as in FFS), only a list of clean segments

LFS Segment Cleaning

- Which segments to clean?
  - Keep estimate of free space in each segment to help find segments with lowest utilization
  - Always start by looking for segment with utilization=0, since those are trivial to clean…
  - If utilization of segments being cleaned is U:
    - » write cost = (total bytes read & written)/(new data written) = 2/(1-U) (unless U is 0)
    - » write cost increases as U increases: U = .9 => cost = 20!
    - » Need a cost of less than 4 to 10; => U of less than .75 to .45
- How to clean a segment?
  - Segment summary block contains map of the segment
  - Must list every i-node and file block
  - For file blocks you need {i-number, block #}

Analysis and Evolution of Journaling File Systems

- Write-ahead logging: commit data by writing it to log, synchronously and sequentially
- Unlike LFS, then later moved data to its normal (FFS-like) location – this write is called *checkpointing* and like segment cleaning, it makes room in the (circular) journal
- Better for random writes, slightly worse for big sequential writes
- All reads go the the fixed location blocks, not the journal, which is only read for crash recovery and checkpointing
- Much better than FFS (fsck) for crash recovery (covered below) because it is much faster
- Ext3/ReiserFS/Ext4 filesystems are the main ones in Linux

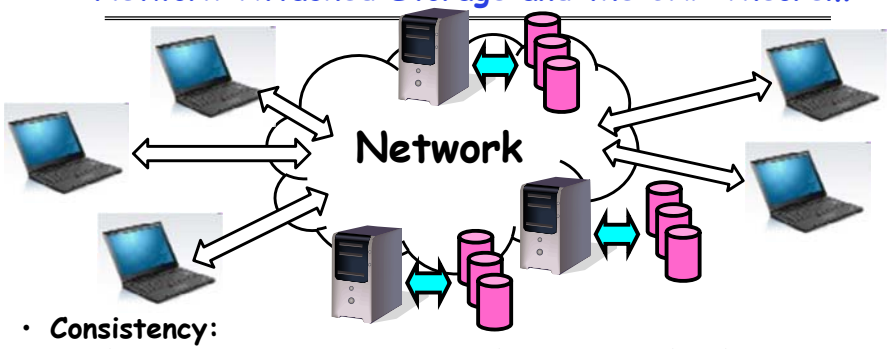
Three modes for a JFS

- *Writeback mode*:
  - Journal only metadata
  - Write back data and metadata independently
  - Metadata may thus have dangling references after a crash (if metadata written before the data with a crash in between)
- *Ordered mode*:
  - Journal only metadata, but always write data blocks before their referring metadata is journaled
  - This mode generally makes the most sense and is used by Windows NTFS and IBM's JFS
- *Data journaling mode*:
  - Write both data and metadata to the journal
  - Huge increase in journal traffic; plus have to write most blocks twice, once to the journal and once for checkpointing

What about remote file systems?

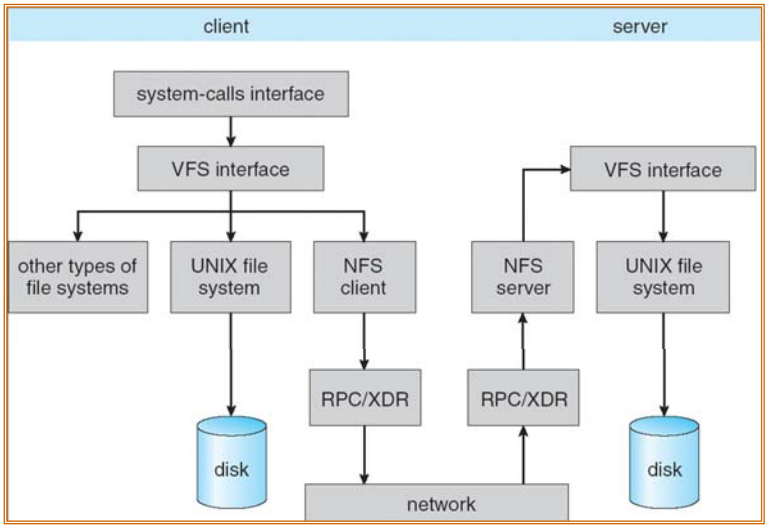
- Remote File System:
  - Storage available over a network
  - Local storage is only a cache on permanent storage
- Advantages?
  - Someone else worries about keeping data safe
  - Data Accessible from multiple physical locations
- Disadvantages?
  - Performance – may take one or more network roundtrips to fetch data
  - Privacy: your data is available over the network, others can possibly see your data
  - Integrity: without sufficient protections, others can overwrite/delete your data

Network-Attached Storage and the CAP Theorem

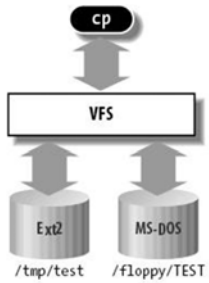


- Consistency:
  - Changes appear to everyone in the same serial order
- Availability:
  - Can get a result at any time
- Partition-Tolerance
  - System continues to work even when network becomes partitioned
- Consistency, Availability, Partition-Tolerance (CAP) Theorem: Cannot have all three at same time
  - Otherwise known as "Brewer's Theorem"

Schematic View of NFS Architecture



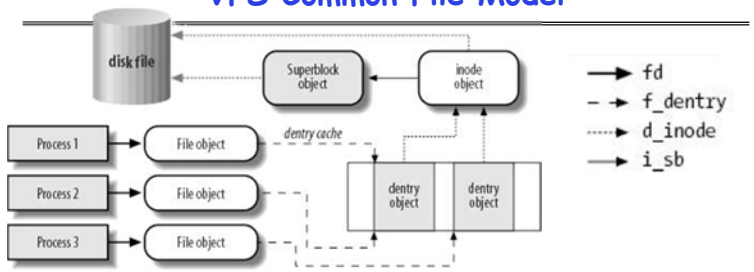
Virtual Filesystem Switch (VFS)




```
inf = open("/floppy/TEST", O_RDONLY, 0);
outf = open("/tmp/test",
       O_WRONLY|O_CREAT|O_TRUNC, 0600);
do {
    i = read(inf, buf, 4096);
    write(outf, buf, i);
} while (i);
close(outf);
close(inf);
```

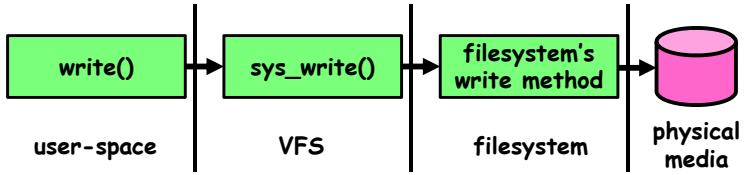
- VFS: Virtual abstraction similar to local file system
  - Provides virtual superblocks, inodes, files, etc
  - Compatible with a variety of local and remote file systems
    - » provides object-oriented way of implementing file systems
- VFS allows the same system call interface (the API) to be used for different types of file systems
  - The API is to the VFS interface, rather than any specific type of file system

VFS Common File Model



- Four primary object types for VFS:
  - superblock object: represents a specific mounted filesystem
  - inode object: represents a specific file
  - dentry object: represents a directory entry
  - file object: represents open file associated with process
- There is no specific directory object (VFS treats directories as files)
- May need to fit the model by faking it
  - Example: make it look like directories are files
  - Example: make it look like have inodes, superblocks, etc.

Linux VFS



- An operations object is contained within each primary object type to set operations of specific filesystems
  - "super_operations": methods that kernel can invoke on a specific filesystem, i.e. `write_inode()` and `sync_fs()`.
  - "inode_operations": methods that kernel can invoke on a specific file, such as `create()` and `link()`
  - "dentry_operations": methods that kernel can invoke on a specific directory entry, such as `d_compare()` or `d_delete()`
  - "file_operations": methods that process can invoke on an open file, such as `read()` and `write()`
- There are a lot of operations
  - You need to read Bovet Chapter 12 and Love Chapter 13

Summary (1/2)

- Multilevel Indexed Scheme
  - Inode contains file info, direct pointers to blocks,
  - indirect blocks, doubly indirect, etc..
- Cray DEMOS: optimization for sequential access
  - Inode holds set of disk ranges, similar to segmentation
- 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
- Important system properties
  - Availability: how often is the resource available?
  - Durability: how well is data preserved against faults?
  - Reliability: how often is resource performing correctly?

Summary (2/2)

- Log Structured File system (LFS)
  - The Log *is* the file system
  - All updates written sequentially in the log
  - Inode map tracks where inodes lie in the log
- Journaling File System (JFS, Ext3, …)
  - Use of log to help durability
  - Primary storage in read-optimized format
- Distributed File System:
  - Transparent access to files stored on a remote disk
  - Caching for performance
- VFS: Virtual File System layer
  - Provides mechanism which gives same system call interface for different types of file systems
  - More Next Time!