CS162
Operating Systems and Systems Programming
Lecture 23

Filesystems 3: Filesystem Case Studies (Con't), Buffer Cache, Reliability

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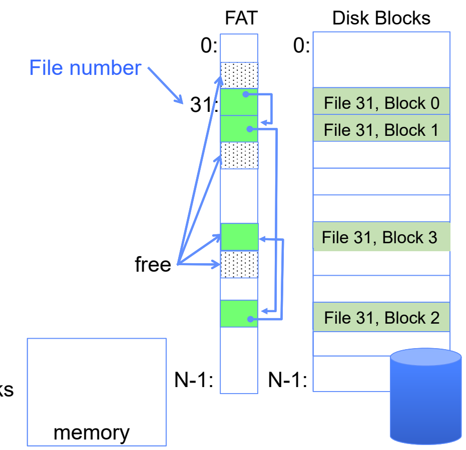
Recall: FAT Properties

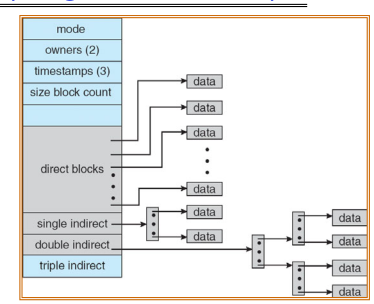
- File is collection of disk blocks (Microsoft calls them "clusters")
- FAT is array of integers mapped 1-1 with disk blocks
  - Each integer is either:
    - » Pointer to next block in file; or
    - » End of file flag; or
    - » Free block flag
- File Number is index of root of block list for the file
  - Follow list to get block #
  - Directory must map name to block number at start of file
- But: Where is FAT stored?
  - Beginning of disk, before the data blocks
  - Usually 2 copies (to handle errors)



CASE STUDY: BERKELEY FAST FILE SYSTEM (FFS)

Recall: Multilevel Indexed Files (Original 4.1 BSD)

- Sample file in multilevel indexed format:
  - 10 direct ptrs, 1K blocks
  - 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!)

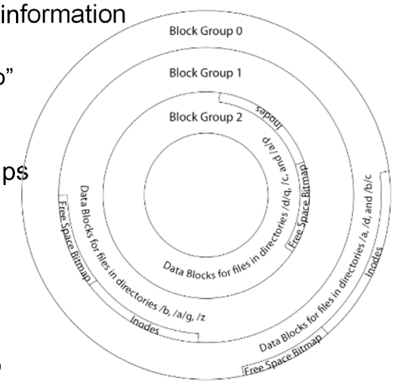


Recall: FFS Changes in Inode Placement: Motivation

- In early UNIX and DOS/Windows' FAT file system, headers stored in special array in outermost cylinders
  - Fixed size, set when disk is formatted
    - » At formatting time, a fixed number of inodes are created
    - » Each is given a unique number, called an "inumber"
- Problem #1: Inodes all in one place (outer tracks)
  - Head crash potentially destroys all files by destroying inodes
  - Inodes not close to the data that the point to
    - » To read a small file, seek to get header, seek back to data
- Problem #2: 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?
  - Makes it hard to optimize for performance

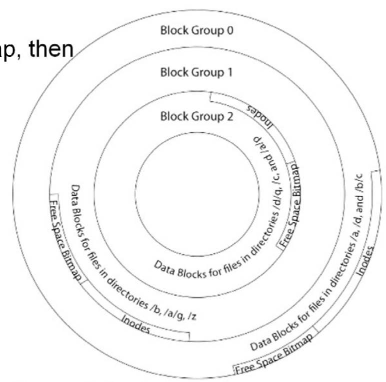
FFS Locality: Block Groups

- The UNIX BSD 4.2 (FFS) distributed the header information (inodes) 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 very fast
- File system volume divided into set of block groups
  - Close set of tracks
- Data blocks, metadata, and free space interleaved within block group
  - Avoid huge seeks between user data and system structure
- Put directory and its files in common block group

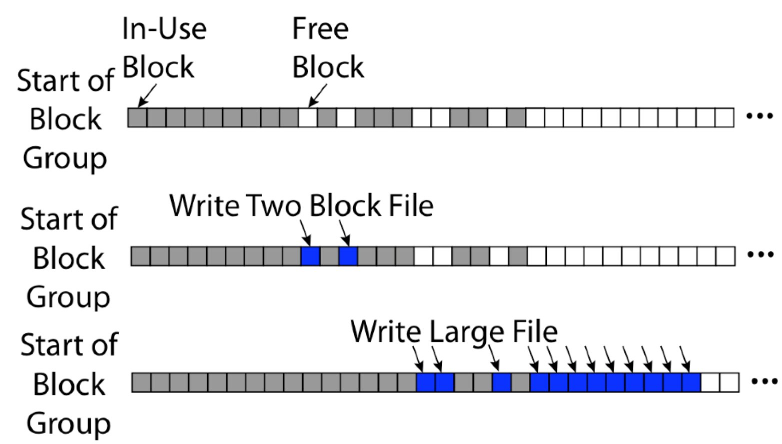


FFS Locality: Block Groups (Con't)

- First-Free allocation of new file blocks
  - To expand file, first try successive blocks in bitmap, then choose new range of blocks
  - Few little holes at start, big sequential runs at end of group
  - Avoids fragmentation
  - Sequential layout for big files
- Important: keep 10% or more free!
  - Reserve space in the Block Group
- Summary: FFS Inode Layout Pros
  - 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)

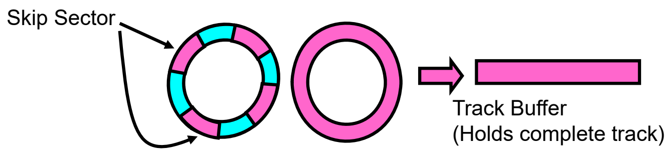


UNIX 4.2 BSD FFS First Fit Block Allocation



Attack of the Rotational Delay

- Problem 3: 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!



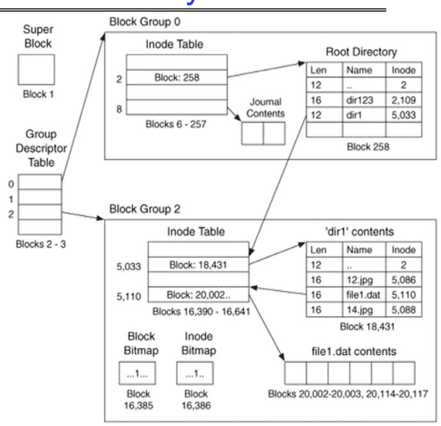
  - Solution1: Skip sector positioning ("interleaving")
    - » Place the blocks from one file on every other block of a track: give time for processing to overlap rotation
    - » Can be done by OS or in modern drives by the disk controller
  - Solution 2: Read ahead: read next block right after first, 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
- Modern disks + controllers do many things "under the covers"
  - Track buffers, elevator algorithms, bad block filtering

UNIX 4.2 BSD FFS

- Pros
  - Efficient storage for both small and large files
  - Locality for both small and large files
  - Locality for metadata and data
  - No defragmentation necessary!
- Cons
  - Inefficient for tiny files (a 1 byte file requires both an inode and a data block)
  - Inefficient encoding when file is mostly contiguous on disk
  - Need to reserve 10-20% of free space to prevent fragmentation

Linux Example: Ext2/3 Disk Layout

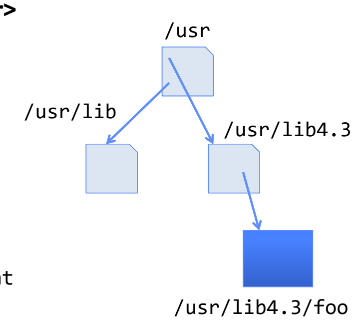
- Disk divided into block groups
  - Provides locality
  - Each group has two block-sized bitmaps (free blocks/inodes)
  - Block sizes settable at format time: 1K, 2K, 4K, 8K…
- Actual inode structure similar to 4.2 BSD
  - with 12 direct pointers
- Ext3: Ext2 with Journaling
  - Several degrees of protection with comparable overhead
  - We will talk about Journalling later



- Example: create a `file1.dat` under `/dir1/` in Ext3

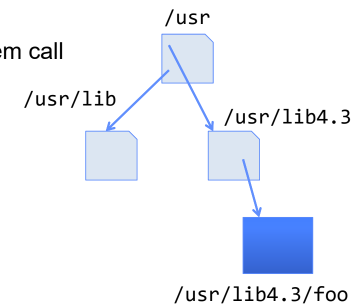
Recall: Directory Abstraction

- Directories are specialized files
  - Contents: **List of pairs <file name, file number>**
- System calls to access directories
  - `open` / `creat` traverse the structure
  - `mkdir` /`rmdir` add/remove entries
  - `link` / `unlink` (`rm`)
- libc support
  - `DIR * opendir (const char *dirname)`
  - `struct dirent * readdir (DIR *dirstream)`
  - `int readdir_r (DIR *dirstream, struct dirent *entry, struct dirent **result)`



Hard Links

- Hard link
  - Mapping from name to file number in the directory structure
  - First hard link to a file is made when file created
  - Create extra hard links to a file with the link() system call
  - Remove links with unlink() system call
- When can file contents be deleted?
  - When there are no more hard links to the file
  - Inode maintains reference count for this purpose

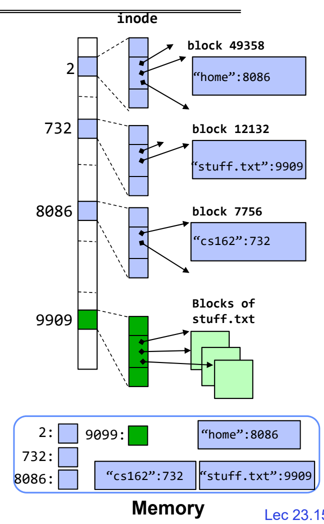


Soft Links (Symbolic Links)

- Soft link or Symbolic Link or Shortcut
  - Directory entry contains the path and name of the file
  - Map one name to another name
- Contrast these two different types of directory entries:
  - Normal directory entry: <file name, file #>
  - Symbolic link: <file name, dest. file name>
- OS looks up destination file name **each time** program accesses source file name
  - Lookup can fail (error result from **`open`**)
- Unix: Create soft links with **`symlink`** syscall

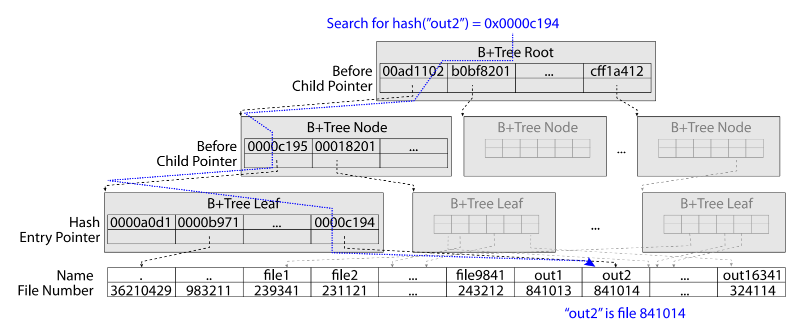
Directory Traversal

- What happens when we open `/home/cs162/stuff.txt`?
- "/" - inumber for root inode configured into kernel, say 2
  - Read inode 2 from its position in inode array on disk
  - Extract the direct and indirect block pointers
  - Determine block that holds root directory (say block 49358)
  - Read that block, scan it for "home" to get inumber for this directory (say 8086)
- Read inode 8086 for /home, extract its blocks, read block (say 7756), scan it for "cs162" to get its inumber (say 732)
- Read inode 732 for /home/cs162, extract its blocks, read block (say 12132), scan it for "stuff.txt" to get its inumber, say 9909
- Read inode 9909 for /home/cs162/stuff.txt
- Set up file description to refer to this inode so reads / write can access the data blocks referenced by its direct and indirect pointers
- **Check permissions on the final inode and each directory's inode…**



Large Directories: B-Trees (dirhash)

in FreeBSD, NetBSD, OpenBSD



Administrivia

- Homework 5: Due April 23rd
- Project 3: Design reviews this week
- Midterm 3: April 25th
  - Everything fair game with focus on last 1/3 of class
  - Three *hand-written* cheat-sheets, double sided
- Class attendance: No credit for people who use the same photo!
- Last chance to suggest topics for final lecture!

https://tinyurl.com/25ep5ep3

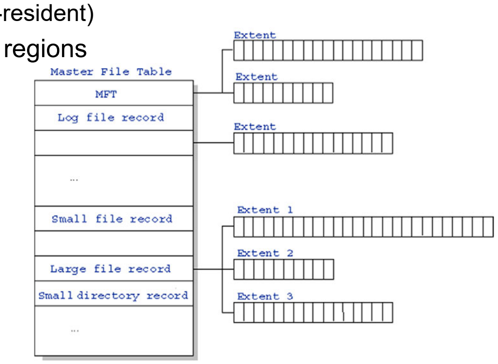
CASE STUDY: WINDOWS NTFS

New Technology File System (NTFS)

- Default on modern Windows systems
- Variable length extents
  - Rather than fixed blocks
- Instead of FAT or inode array: Master File Table
  - Like a database, with max 1 KB size for each table entry
  - Everything (almost) is a sequence of <attribute:value> pairs
    - » Meta-data and data
- Each entry in MFT contains metadata and:
  - File's data directly (for small files)
  - A list of *extents* (start block, size) for file's data
  - For big files: pointers to other MFT entries with *more* extent lists

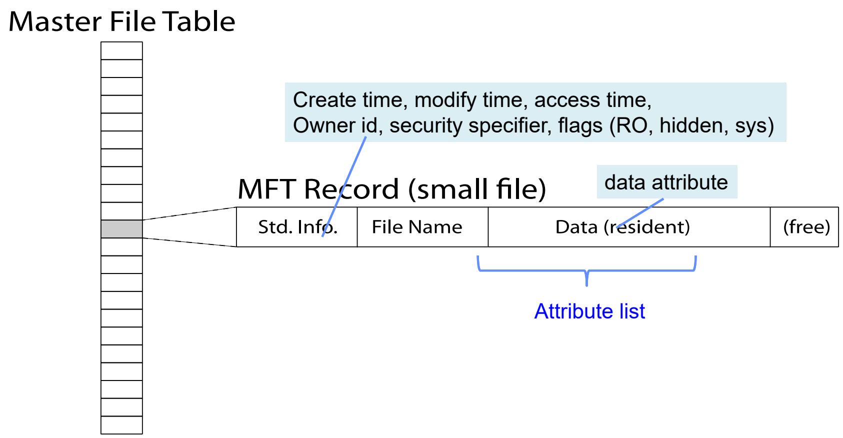
NTFS

- Master File Table
  - Database with Flexible 1KB entries for metadata/data
  - Variable-sized attribute records (data or metadata)
  - Extend with variable depth tree (non-resident)
- Extents – variable length contiguous regions
  - Block pointers cover runs of blocks
  - Similar approach in Linux (ext4)
  - File create can provide hint as to size of file
- Journaling for reliability
  - Discussed later

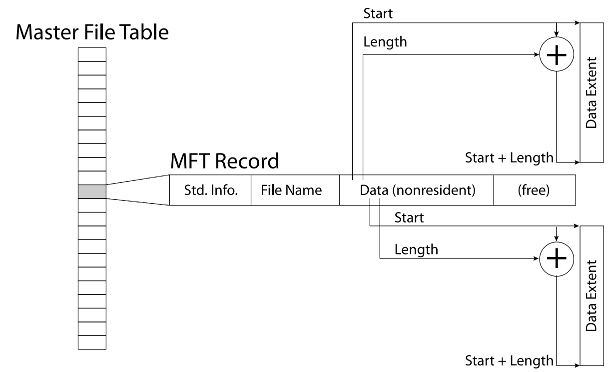


http://ntfs.com/ntfs-mft.htm

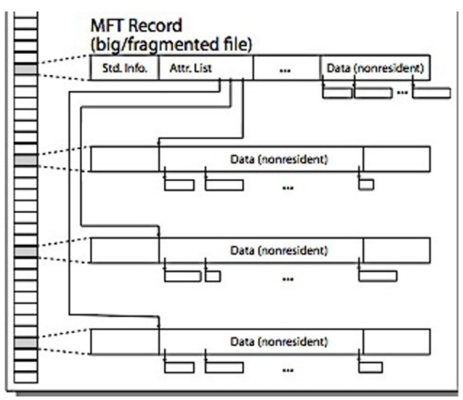
NTFS Small File: Data stored with Metadata



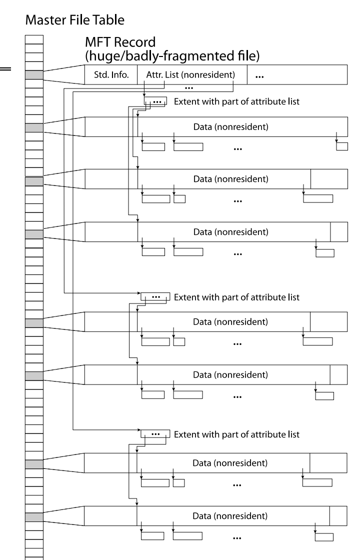
NTFS Medium File: Extents for File Data



NTFS Large File: Pointers to Other MFT Records



NTFS Huge, Fragmented File: Many MFT Records

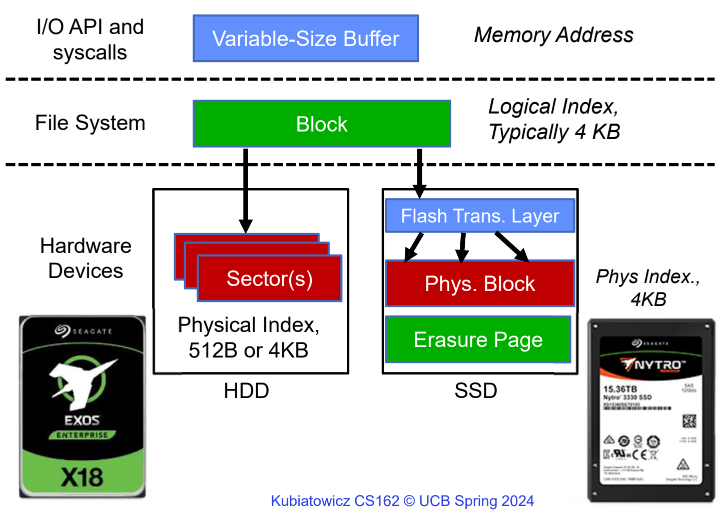


NTFS Directories

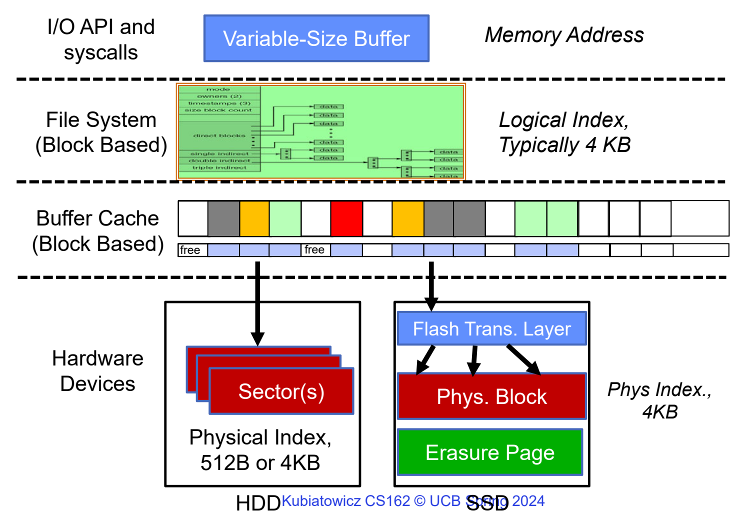
- Directories implemented as B Trees
- File's number identifies its entry in MFT
- MFT entry always has a file name attribute
  - Human readable name, file number of parent dir
- Hard link? Multiple file name attributes in MFT entry

THE BUFFER CACHE

Recall: From Storage to File Systems



Need for Cache Between FileSystem and Devices



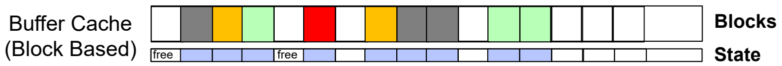
Not block-sized or block-aligned access

Reuse of inodes, indirect blocks, data blocks

Speed up access to file system path and data

Apparent speed and flexibility is greater because of Buffer Cache

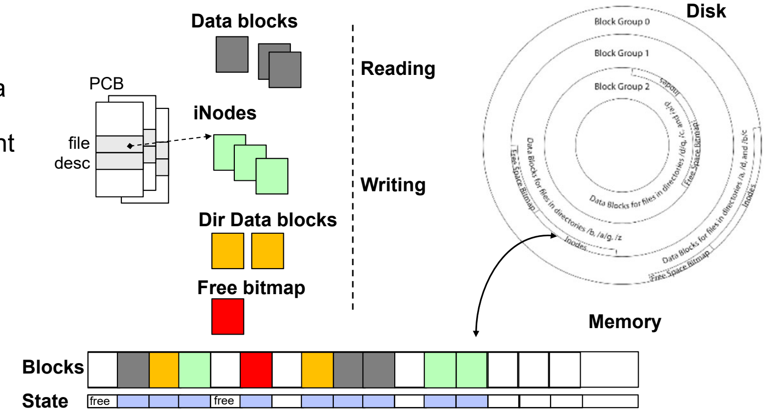
Buffer Cache: Motivation



- Kernel *must* copy disk blocks to memory (somewhere) to access their contents and write them back if modified
  - Could be data blocks, inodes, directory contents, etc.
  - Possibly dirty (modified and not yet written back)
- Key Idea: Exploit locality by caching disk 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 (with modifications not on disk)

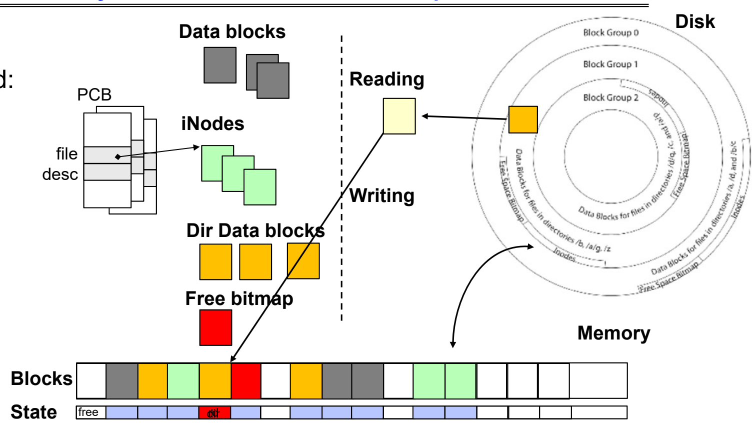
File System Buffer Cache

- OS implements a cache of disk blocks for efficient access to data, directories, inodes, freemap



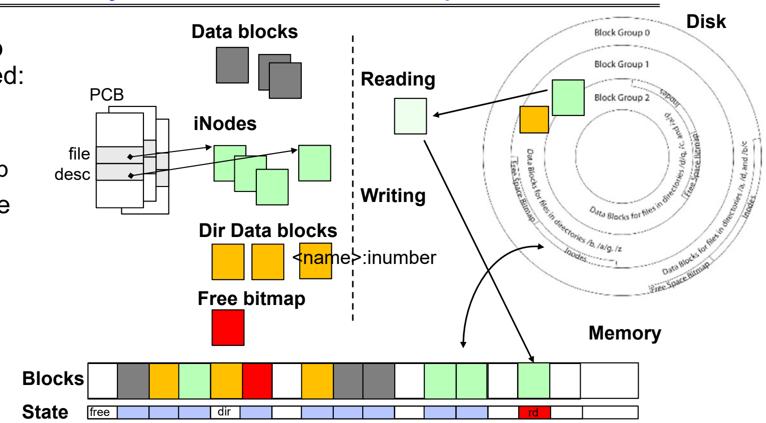
File System Buffer Cache: open

- Directory lookup repeat as needed:
  - load block of directory
  - search for map



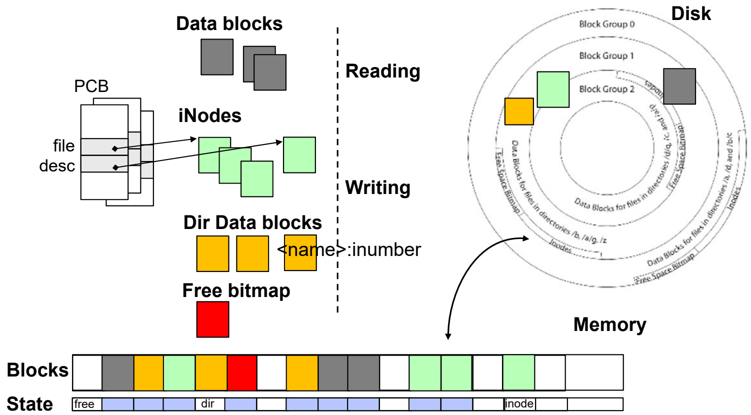
File System Buffer Cache: open

- Directory lookup repeat as needed:
  - load block of directory
  - search for map
- Create reference via open file descriptor



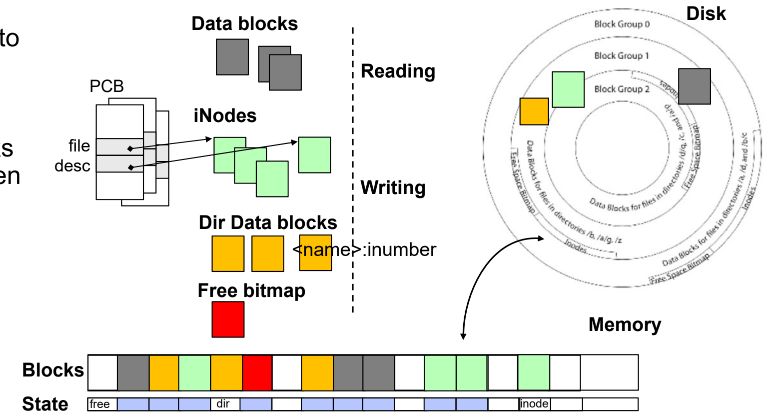
File System Buffer Cache: Read?

- Read Process
  - From inode, traverse index structure to find data block
  - load data block
  - copy all or part to read data buffer



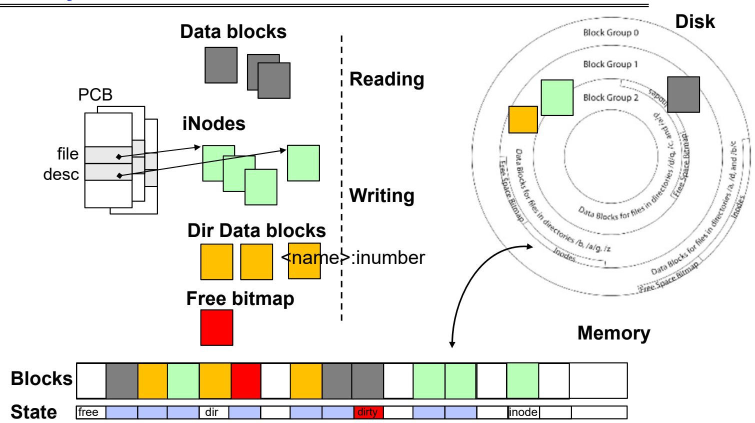
File System Buffer Cache: Write?

- Process similar to read, but may allocate new blocks (update free map), blocks need to be written back to disk; inode?



File System Buffer Cache: Eviction?

- Blocks being written back to disc go through a transient state



Buffer Cache Discussion

- Implemented entirely in OS software
  - Unlike memory caches and TLB
- Blocks go through transitional states between free and in-use
  - Being read from disk, being written to disk
  - Other processes can run, etc.
- Blocks are used for a variety of purposes
  - inodes, data for dirs and files, freemap
  - OS maintains pointers into them
- Termination – e.g., process exit – open, read, write
- Replacement – what to do when it fills up?

File System Caching

- Replacement policy? LRU
  - Can afford overhead full LRU implementation
  - 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
  - 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

File System Prefetching

- 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
  - Elevator algorithm can efficiently interleave prefetches from concurrent applications
- How much to prefetch?
  - Too much prefetching imposes delays on requests by other applications
  - Too little prefetching causes many seeks (and rotational delays) among concurrent file requests

Delayed Writes

- Buffer cache is a writeback cache (writes are termed "Delayed Writes")
- `write()` copies data from user space to kernel buffer cache
  - Quick return to user space
- `read()` is fulfilled by the cache, so `reads` see the results of `writes`
  - Even if the data has not reached disk
- When does data from a `write` syscall finally reach disk?
  - When the buffer cache is full (e.g., we need to evict something)
  - When the buffer cache is flushed periodically (in case we crash)

Delayed Writes (Advantages)

- Performance advantage: return to user quickly without writing to disk!
- Disk scheduler can efficiently order lots of requests
  - Elevator Algorithm can rearrange writes to avoid random seeks
- Delay block allocation:
  - May be able to allocate multiple blocks at same time for file, keep them contiguous
- Some files never actually make it all the way to disk
  - Many short-lived files!

Buffer Caching vs. Demand Paging

- Replacement Policy?
  - Demand Paging: LRU is infeasible; use approximation (like NRU/Clock)
  - Buffer Cache: LRU is OK
- Eviction Policy?
  - Demand Paging: evict not-recently-used pages when memory is close to full
  - Buffer Cache: write back dirty blocks periodically, even if used recently
    - Why? To minimize data loss in case of a crash

Dealing with Persistent State

- Buffer Cache: write back dirty blocks periodically, even if used recently
  - Why? To minimize data loss in case of a crash
  - Linux does periodic flush every 30 seconds
- Not foolproof! Can still crash with dirty blocks in the cache
  - What if the dirty block was for a directory?
    - Lose pointer to file's inode (leak space)
    - **File system now in inconsistent state ☹**

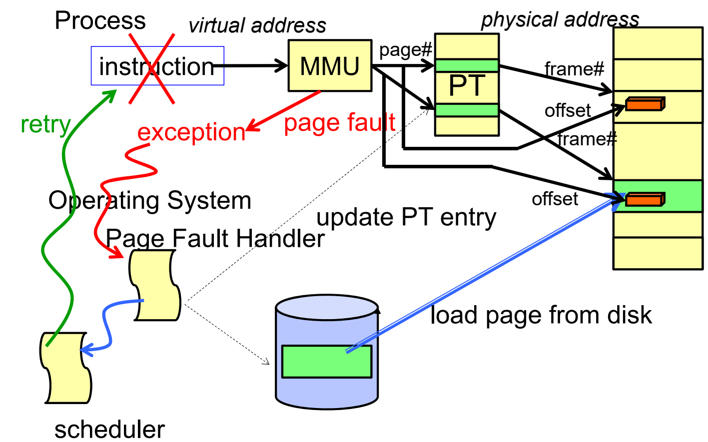
Takeaway: File systems need recovery mechanisms

QUICK ASIDE: MEMORY MAPPED FILES

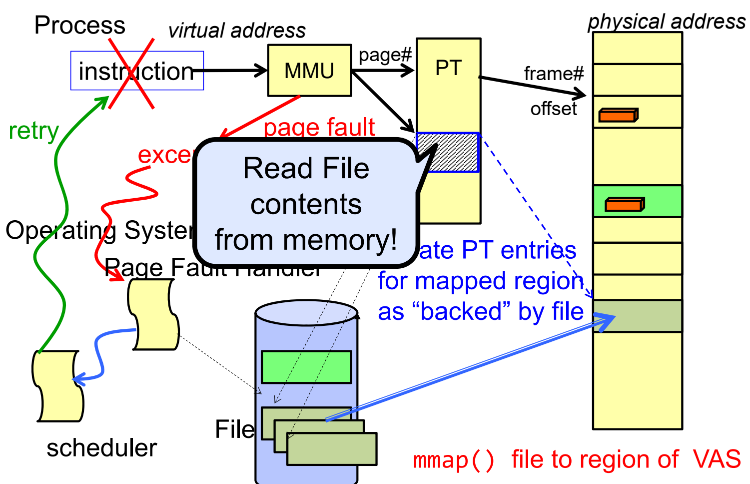
Memory Mapped Files

- Traditional I/O involves explicit transfers between buffers in process address space to/from regions of a file
  - This involves multiple copies into caches in memory, plus system calls
- What if we could “map” the file directly into an empty region of our address space
  - Implicitly “page it in” when we read it
  - Write it and “eventually” page it out
- Data in Buffer Cache already!
- Executable files are treated this way when we `exec` the process!!

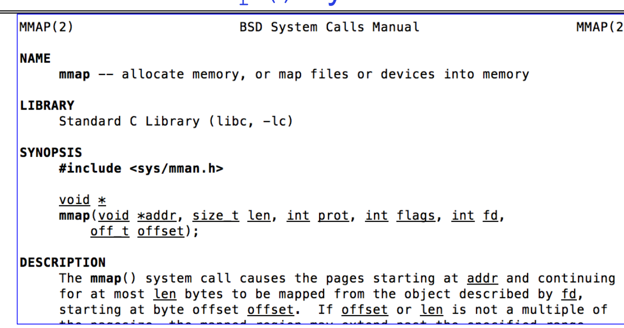
Recall: Who Does What, When?



Using Paging to `mmap()` Files



`mmap()` system call



```
MMAP(2)                  BSD System Calls Manual                  MMAP(2)

NAME
     mmap -- allocate memory, or map files or devices into memory

LIBRARY
     Standard C Library (libc, -lc)

SYNOPSIS
     #include <sys/mman.h>

     void *
     mmap(void *addr, size_t len, int prot, int flags, int fd,
         off_t offset);

DESCRIPTION
     The mmap() system call causes the pages starting at addr and continuing
     for at most len bytes to be mapped from the object described by fd,
     starting at byte offset offset.  If offset or len is not a multiple of
```

- May map a specific region or let the system find one for you
  - Tricky to know where the holes are
- Used both for manipulating files and for sharing between processes

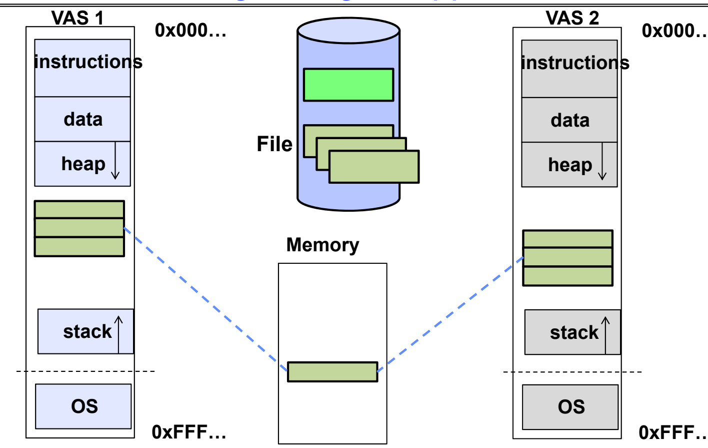
An `mmap()` Example

```
#include <sys/mman.h> /* also stdio.h, stdlib.h, string.h, fcntl.h, unistd.h */

int something = 162;

int main (int argc, char *argv[]) {
  int myfd;
  char *mfile;

  printf("Data  at: %16lx\n", (long
  printf("Heap at : %16lx\n", (long
  printf("Stack at: %16lx\n", (long

  /* Open the file */
  myfd = open(argv[1], O_RDWR | O_CR
  if (myfd < 0) { perror("open failed!");exit(1); }

  /* map the file */
  mfile = mmap(0, 10000, PROT_READ|P
  if (mfile == MAP_FAILED) {perror(

  printf("mmap at : %16lx\n", (long

  puts(mfile);
  strcpy(mfile+20,"Let's write over
  close(myfd);
  return 0;
}
```

```
$ ./mmap test
Data  at:        105d63058
Heap at :     7f8a33c04b70
Stack at:     7fff59e9db10
mmap at :        105d97000
This is line one
This is line two
This is line three
This is line four
```

```
$ cat test
This is line one
ThiLet's write over its line three
This is line four
```


Sharing through Mapped Files



- Also: anonymous memory between parents and children
  – no file backing – just swap space

HOW TO MAKE FILE SYSTEMS MORE *DURABLE*?

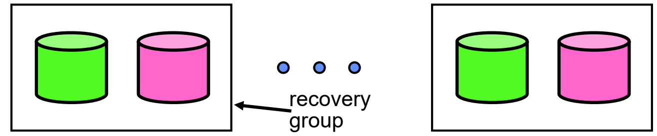
Important "ilities"

- Availability: the probability that the system can accept and process requests
  – Measured in "nines" of probability: e.g. 99.9% probability is "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 Systems more 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 1: Disk Mirroring/Shadowing

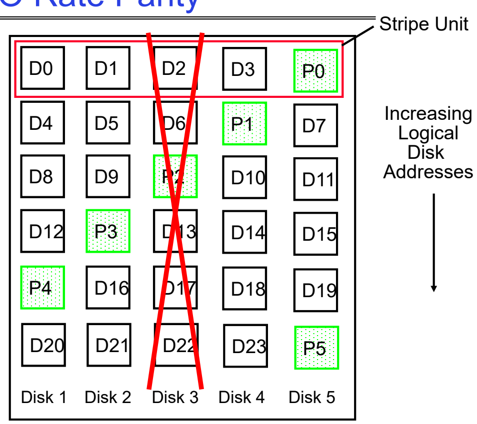


Redundant Array of Inexpensive D
(developed here at Berkeley!)

- Each disk is fully duplicated onto its "shadow"
  – For high I/O rate, high availability environments
  – Most expensive solution: 100% capacity overhead
- Bandwidth sacrificed on write:
  – Logical write = two physical writes
  – Highest bandwidth when disk heads and rotation synchronized (challenging)
- Reads may be optimized
  – Can have two independent reads to same data
- Recovery:
  – Disk failure ⇒ replace disk and copy data to new disk
  – Hot Spare: idle disk attached to system for immediate replacement

RAID 5+: High I/O Rate Parity

- Data stripped across multiple disks
  – Successive blocks stored on successive (non-parity) disks
  – Increased bandwidth over single disk
- Parity block (in green) constructed by XORing data blocks in stripe
  – P0=D0⊕D1⊕D2⊕D3
  – Can destroy any one disk and still reconstruct data
- Suppose Disk 3 fails, then can reconstruct: D2=D0⊕D1⊕D3⊕P0

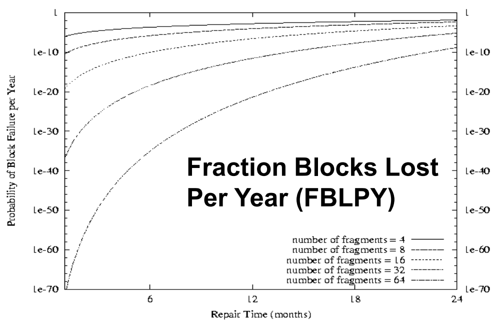


- Can spread information widely across internet for durability
  – RAID algorithms work over geographic scale

RAID 6 and other Erasure Codes

- In general: RAIDX is an "erasure code"
  – Must have ability to know which disks are bad
  – Treat missing disk as an "Erasure"
- Today, disks so big that: RAID 5 not sufficient!
  – Time to repair disk sooooo long, another disk might fail in process!
  – "RAID 6" – allow 2 disks in replication stripe to fail
  – Requires more complex erasure code, such as EVENODD code (see readings)
- More general option for general erasure code: Reed-Solomon codes
  – Based on polynomials in GF(2^k) (I.e. k-bit symbols)
  – m data points define a degree m polynomial; encoding is n points on the polynomial
  – Any m points can be used to recover the polynomial; $n - m$ failures tolerated
- Erasure codes not just for disk arrays. For example, geographic replication
  – E.g., split data into $m = 4$ chunks, generate $n = 16$ fragments and distribute across the Internet
  – Any 4 fragments can be used to recover the original data --- very durable!

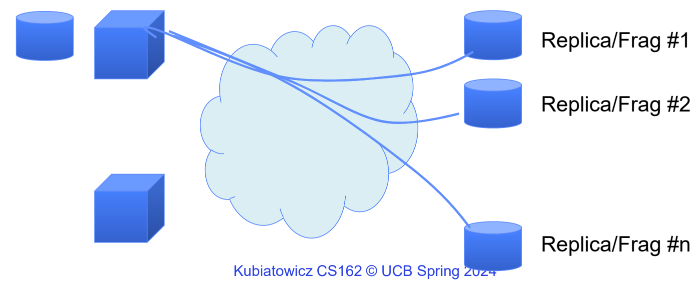
Use of Erasure Coding for High Durability/overhead ratio!



- Exploit law of large numbers for durability!
- 6 month repair, FBLPY with 4x increase in total size of data:
  - Replication (4 copies): 0.03
  - Fragmentation (16 of 64 fragments needed): 10^{-35}

Higher Durability through Geographic Replication

- Highly durable – hard to destroy all copies
- Highly available for reads
  - Simple replication: read any copy
  - Erasure coded: read m of n
- Low availability for writes
  - Can't write if any one replica is not up
  - Or – need relaxed consistency model
- Reliability? – availability, security, durability, fault-tolerance



File System Summary (1/2)

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for size, access and usage patterns
  - Maximize sequential access, allow efficient random access
  - Projects the OS protection and security regime (UGO vs ACL)
- File defined by header, called "inode"
- Naming: translating from user-visible names to actual sys resources
  - Directories used for naming for local file systems
  - Linked or tree structure stored in files
- 4.2 BSD Multilevel Indexed Scheme
  - inode contains file info, direct pointers to blocks, indirect blocks, doubly indirect, etc..
  - NTFS: variable extents not fixed blocks, tiny files data is in header

File System Summary (2/2)

- File layout driven by freespace management
  - Optimizations for sequential access: start new files in open ranges of free blocks, rotational optimization
  - Integrate freespace, inode table, file blocks and dirs into block group
- Deep interactions between mem management, file system, sharing
  - `mmap()`: map file or anonymous segment to memory
- Buffer Cache: Memory used to cache kernel resources, including disk blocks and name translations
  - Can contain "dirty" blocks (blocks yet on disk)