Operating Systems
(Honor Track)

File System 2: File System Case Studies, Buffering

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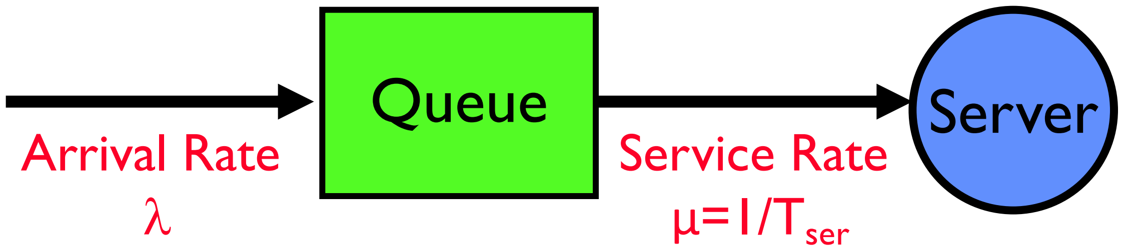
Acknowledgments: Ion Stoica, Berkeley CS 162

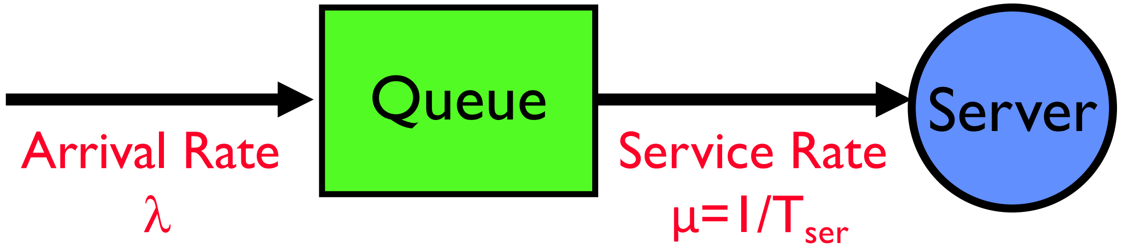
Recap: A Little Queuing Theory: Some Results (1/2)

- Assumptions:
  - System in equilibrium; No limit to the queue
  - Time between successive arrivals is random and memoryless



- Parameters that describe our system:
  - λ: mean number of arriving customers/second
  - T_{ser}: mean time to service a customer ("m")
  - C: squared coefficient of variance = σ^2/m^2
  - μ: service rate = $1/T_{ser}$
  - u: server utilization ($0 \le u \le 1$): $u = \lambda/\mu = \lambda \times T_{ser}$
- Parameters we wish to compute:
  - T_q: Time spent in the queue
  - L_q: Length of queue = $\lambda \times T_q$ (by Little's law)

Recap: A Little Queuing Theory: Some Results (2/2)



- Parameters that describe our system:
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- Parameters we wish to compute:
  - T_q: Time spent in the queue
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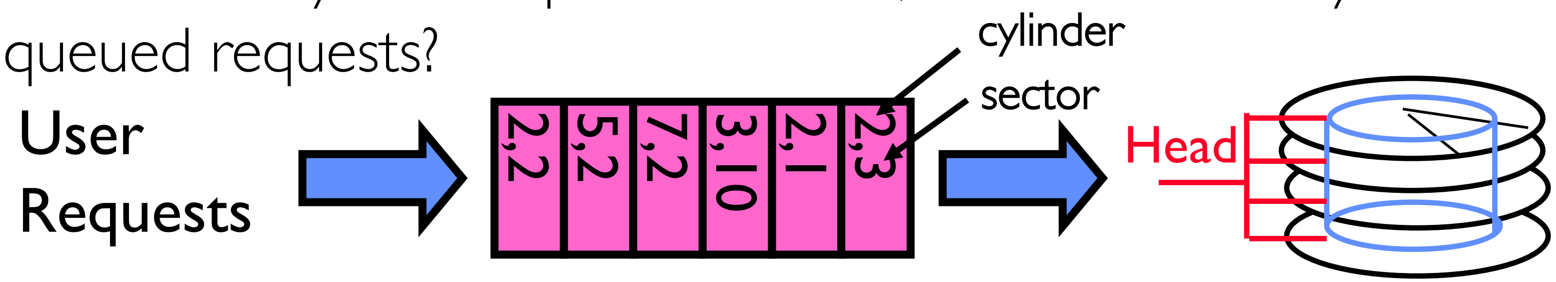
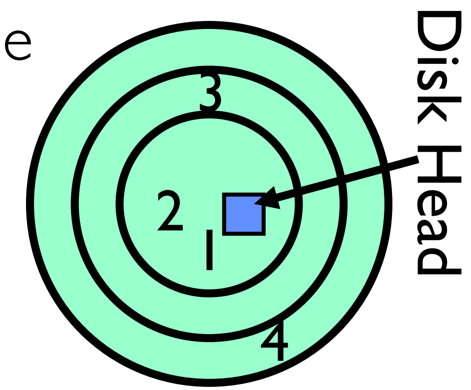
- **Results** (**M**: Poisson arrival process, **1** server):
  - **M**emoryless service time distribution (C = 1): Called an **M/M/1** queue
    - » $T_q = T_{ser} \times u/(1 - u)$
  - **G**eneral service time distribution (no restrictions): Called an **M/G/1** queue
    - » $T_q = T_{ser} \times \frac{1}{2}(1+C) \times u/(1 - u)$

Recap: Disk Scheduling (1/3)

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

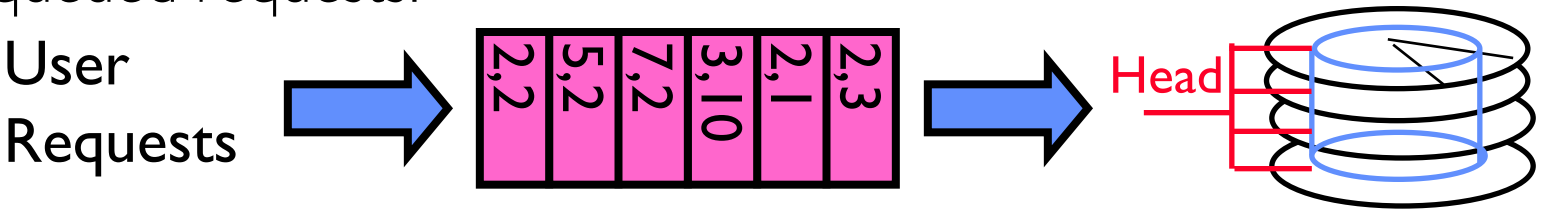


- FIFO Order
  – Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  – Pick the request that's closest on the disk
  – Although called SSTF, today must include rotational delay in calculation, since rotation can be as long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

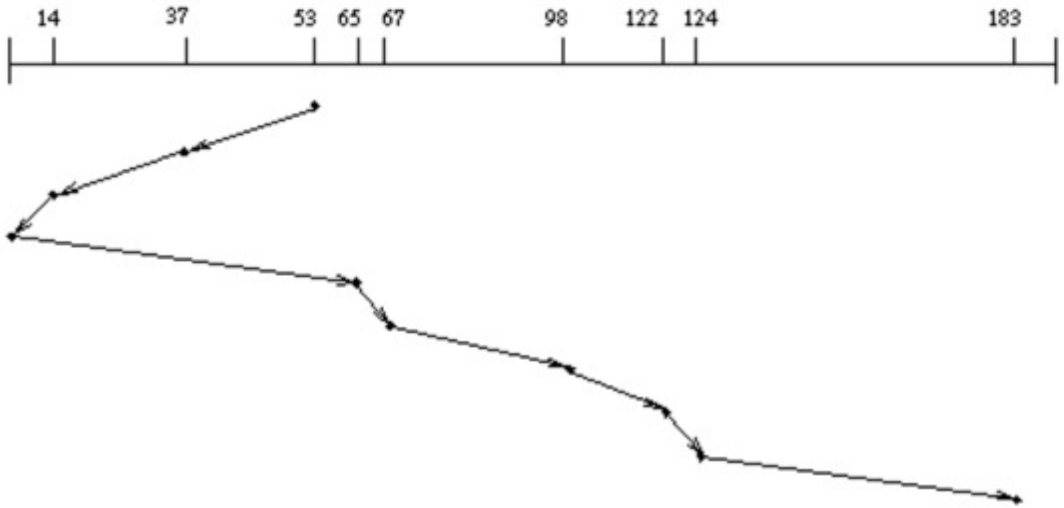


Recap: Disk Scheduling (2/3)

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

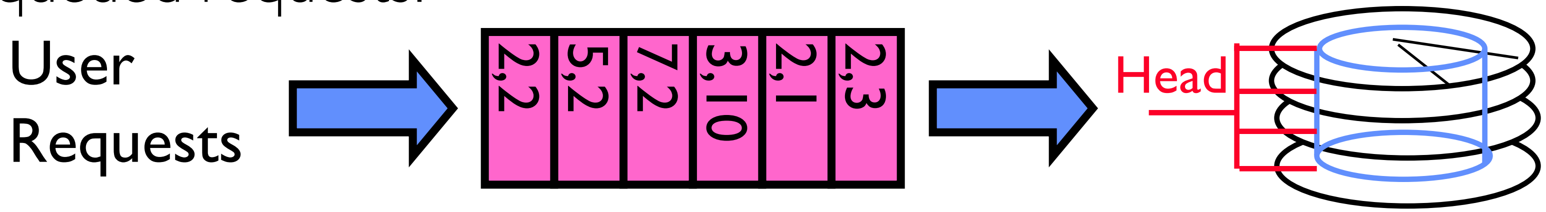


- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  – No starvation, but retains flavor of SSTF

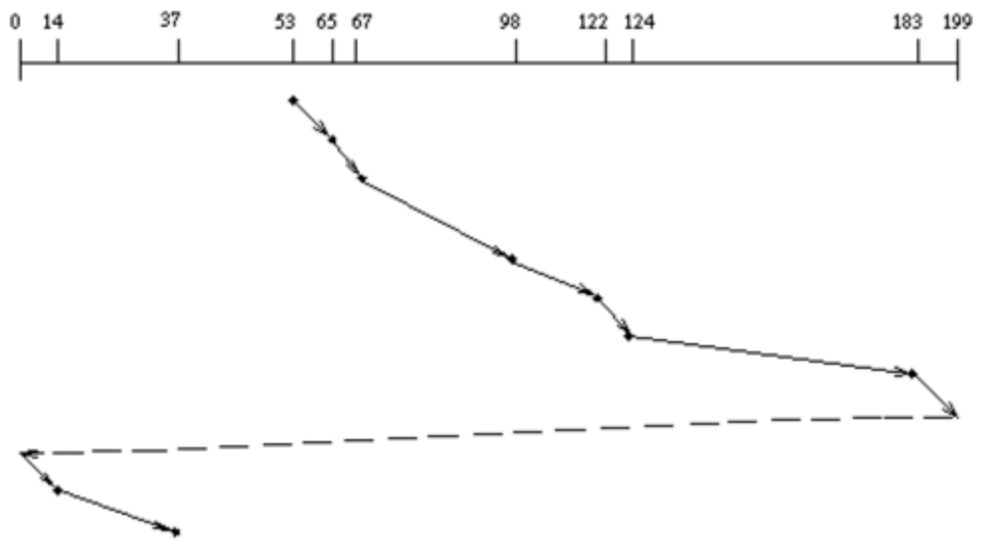


Recap: Disk Scheduling (3/3)

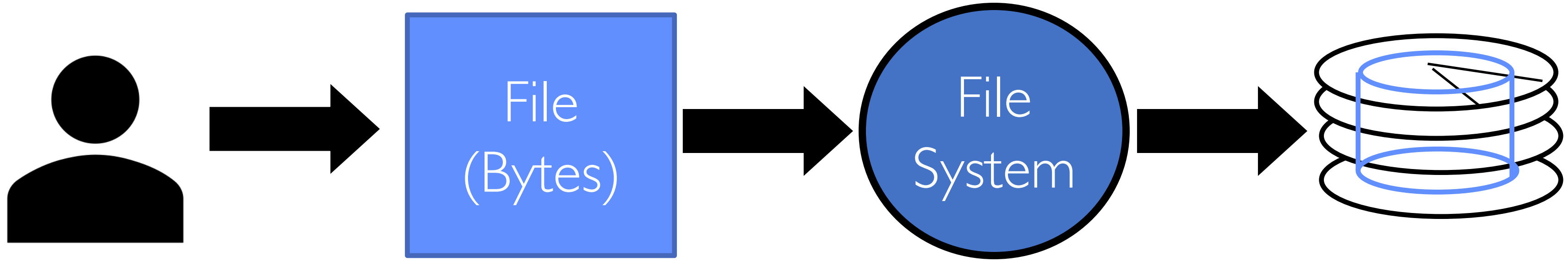
- Disk can do only one request at a time; What order do you choose to do queued requests?



- 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



Recap: Translation from User to System View



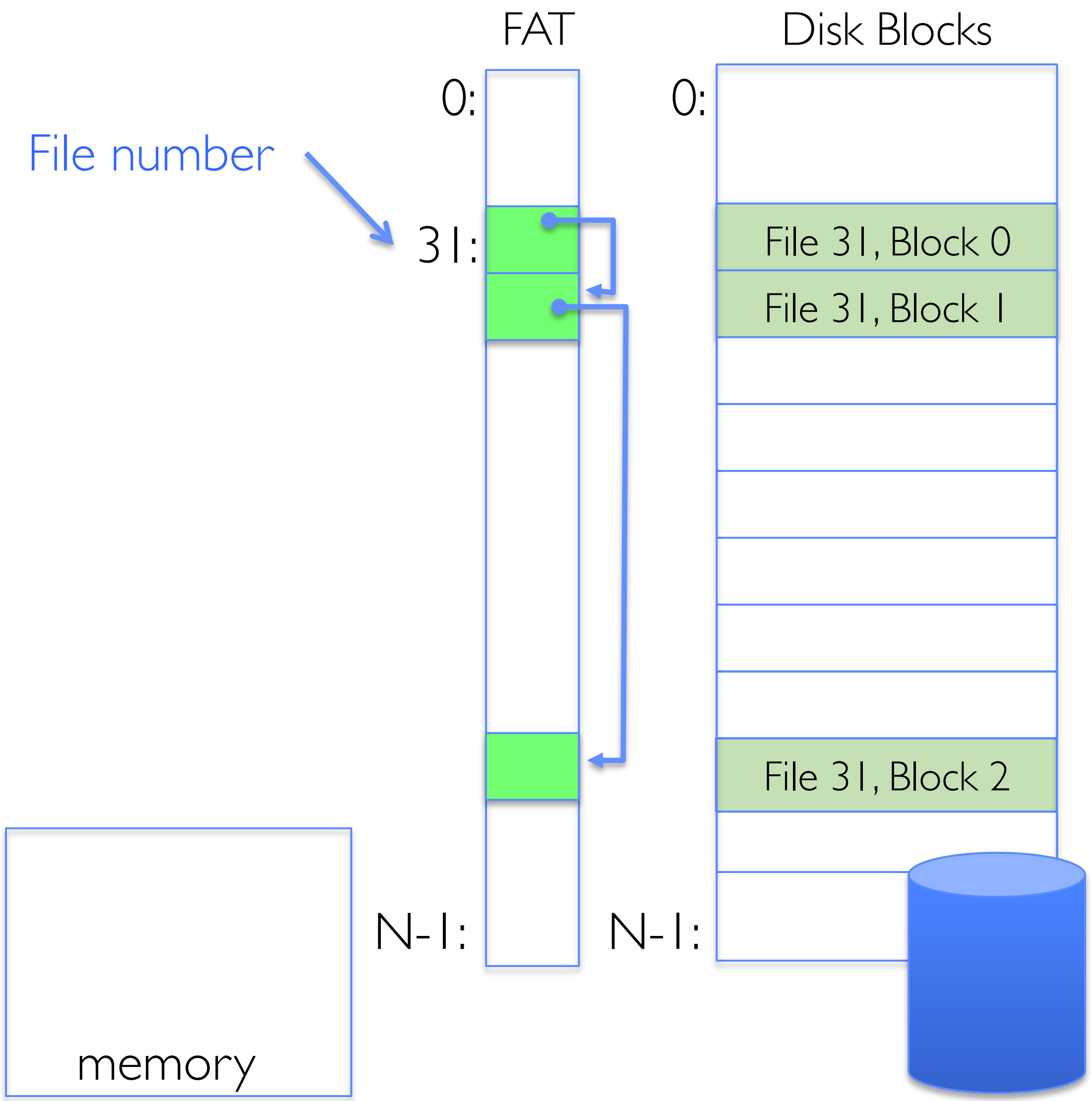
- What happens if user says: "give me bytes 2 – 12?"
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about writing bytes 2 – 12?
  - Fetch block, modify relevant portion, write out block
- Everything inside file system is in terms of whole-size blocks
  - Actual disk I/O happens in blocks
  - read/write smaller than block size needs to translate and buffer

CASE STUDY:
FAT: FILE ALLOCATION TABLE

- MS-DOS, 1977
- Still widely used!

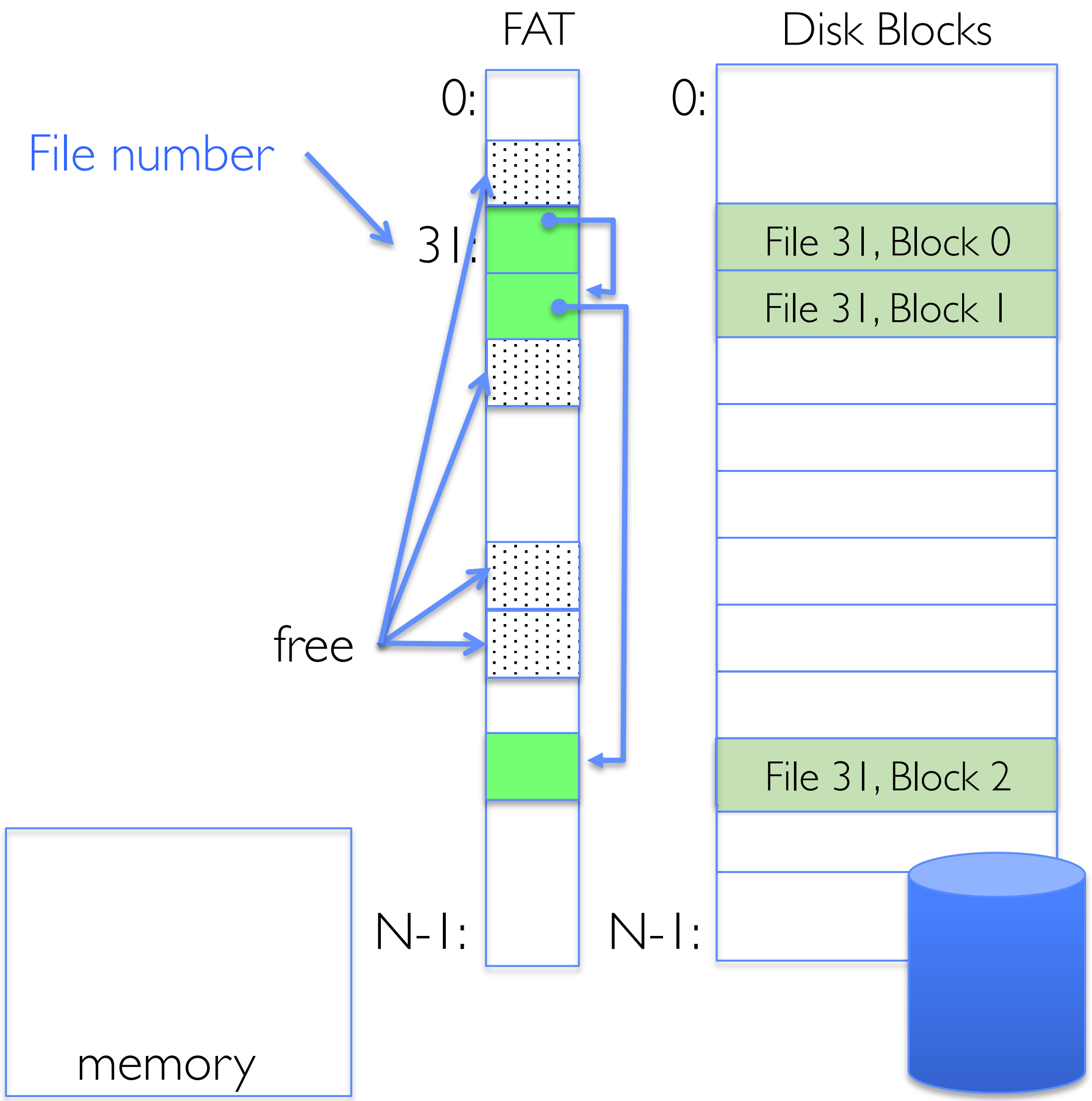
FAT (File Allocation Table)

- Assume (for now) we have a way to translate a path to a "file number"
  - i.e., a directory structure
- Disk Storage is a collection of Blocks
  - Just hold file data (offset o = < B, x >)
- Example: file_read 31, < 2, x >
  - Index into FAT with file number
  - Follow linked list to block
  - Read the block from disk into memory



FAT (File Allocation Table)

- File is a collection of disk blocks
- FAT is a linked list with blocks
- File number is index of root of block list for the file
- File offset: block number and offset within block
- Follow list to get block number
- Unused blocks marked free
  - Could require scan to find
  - Or, could use a free list



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- Follow list to get block number
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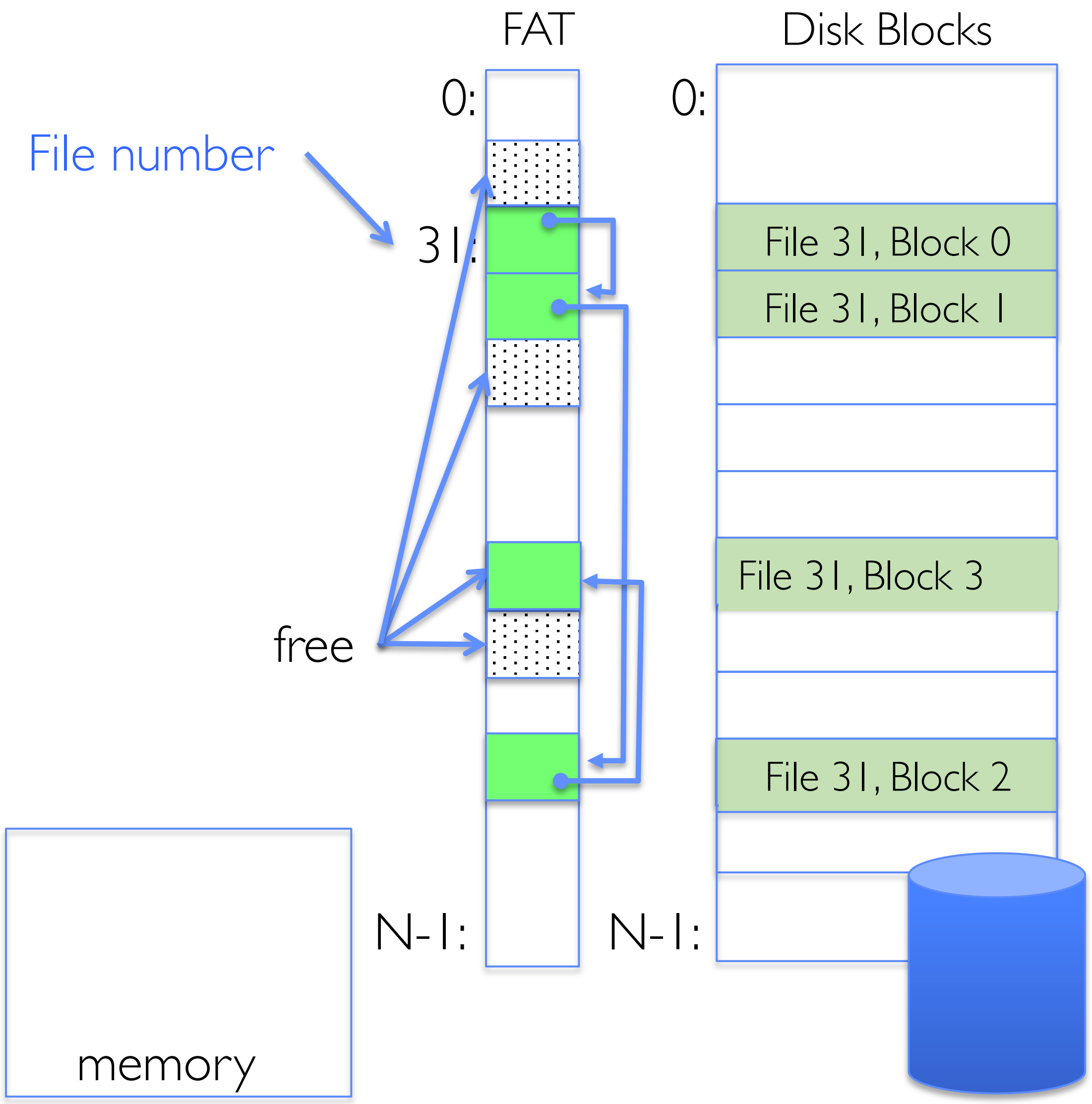
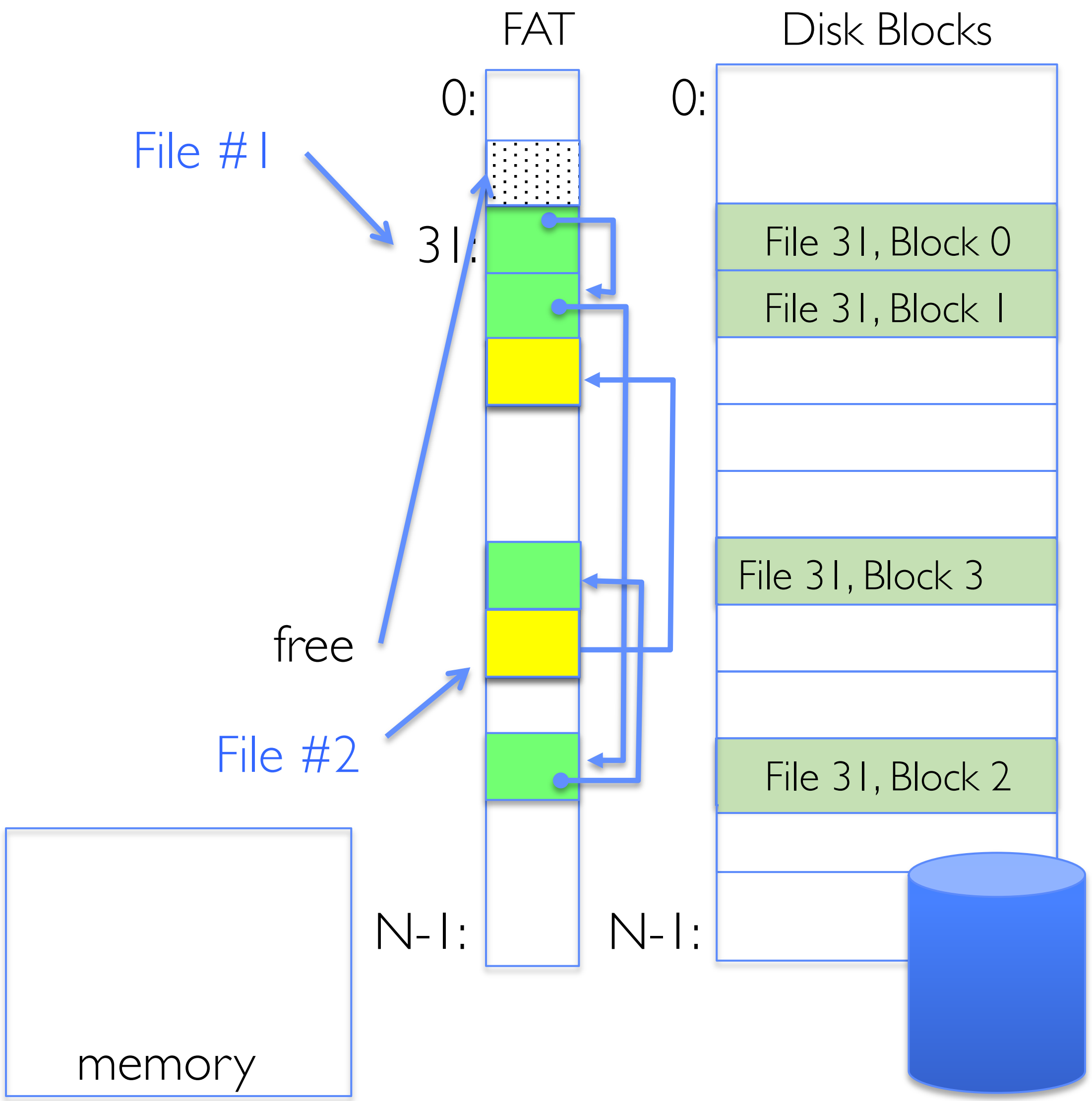
  - Or, could use a free list
- Ex: file_write(31, < 3, y >)
  - Grab free block
  - Linking them into file



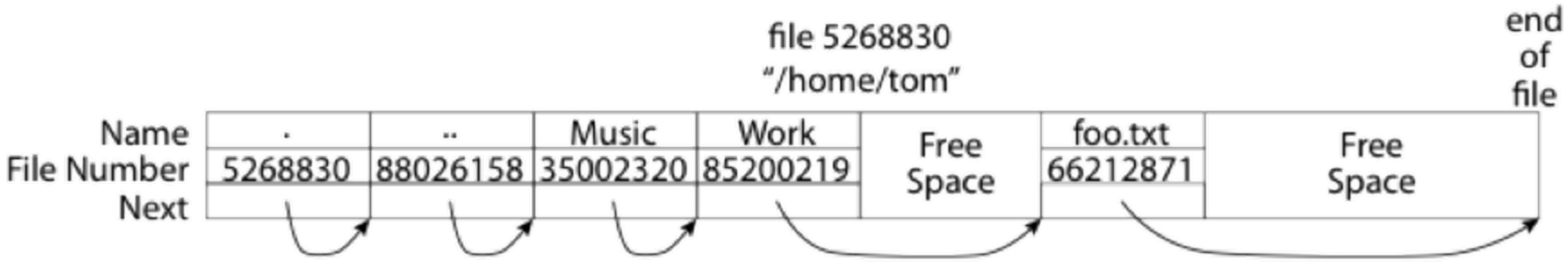
FAT (File Allocation Table)

- Where is FAT stored?
  - On disk
- How to format a disk?
  - Zero the blocks, mark FAT entries “free”
- How to quick format a disk?
  - Mark FAT entries “free”

- Simple: can implement in device firmware



FAT: Directories

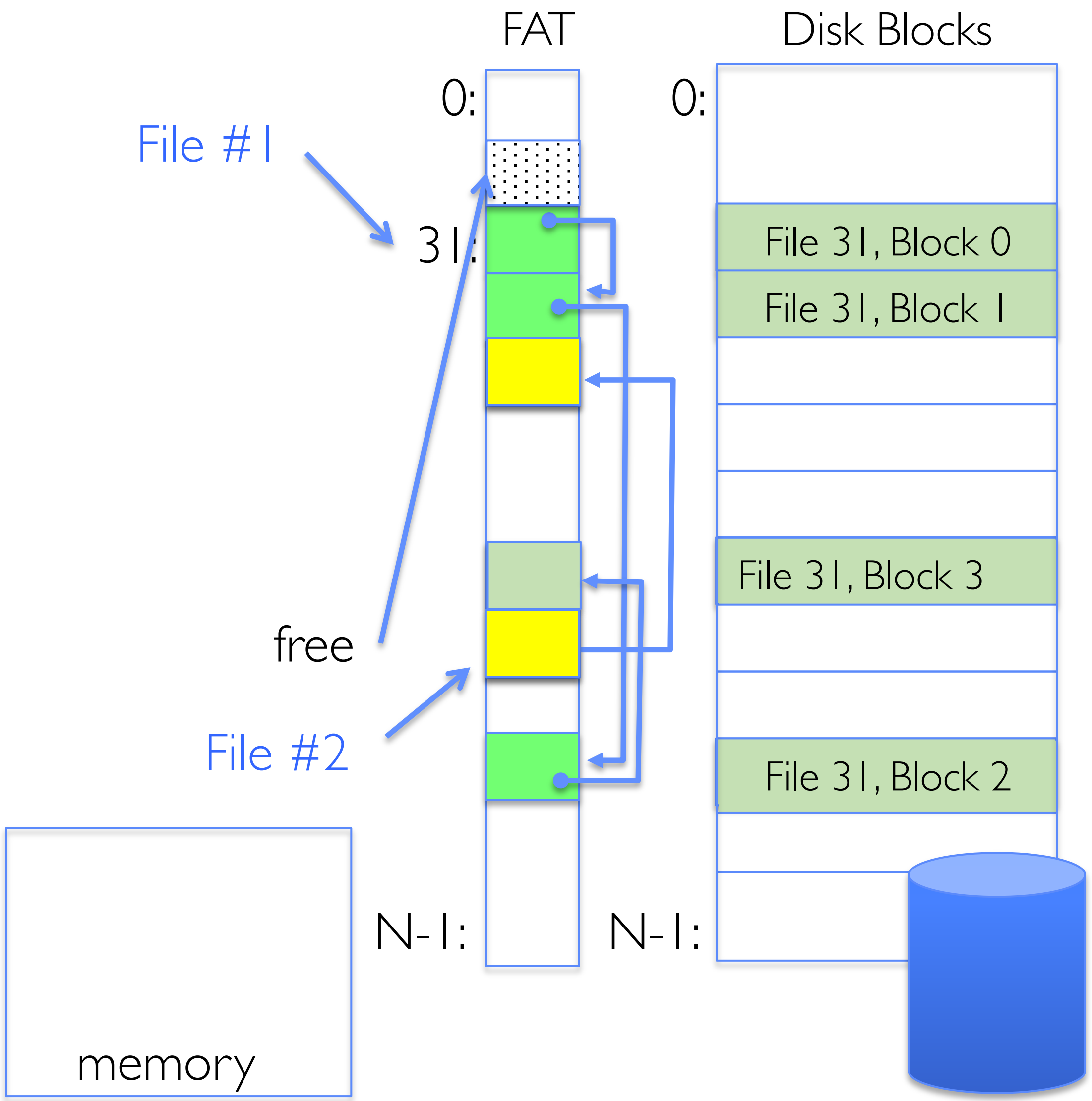


- A directory is a file containing <file_name: file_number> mappings
- Free space for new/deleted entries
- In FAT: file attributes are kept in directory (!!!)
  - Not directly associated with the file itself
- Each directory is a linked list of entries
  - Requires linear search of directory to find particular entry
- Where do you find root directory ("/")?
  - At well-defined place on disk
  - For FAT, this is at block 2 (there are no blocks 0 or 1)

FAT Discussion

Suppose you start with the file number:

- Time to find block?
- Block layout for file?
- Sequential access?
- Random access?
- Fragmentation?
- Small files?
- Big files?



CASE STUDY:
UNIX FILE SYSTEM (BERKELEY FFS)

Inodes in Unix (Including Berkeley FFS)

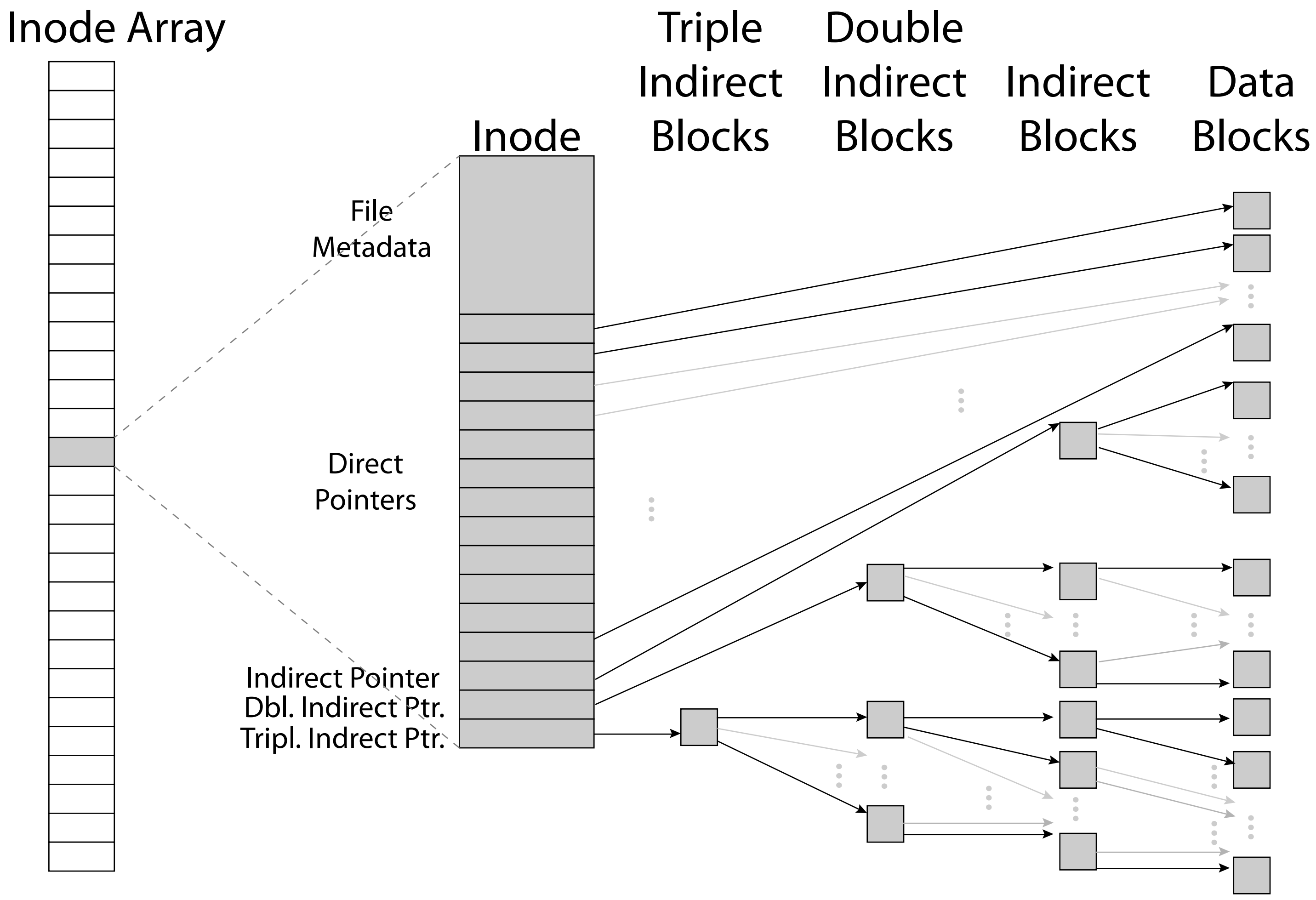
- File Number (inumber) is index into an array of inodes (index structure)

- Each inode corresponds to a file and contains its metadata
  - So, things like read/write permissions are stored with *file,* not in directory (like in FAT)
  - Allows multiple names (directory entries) for a file

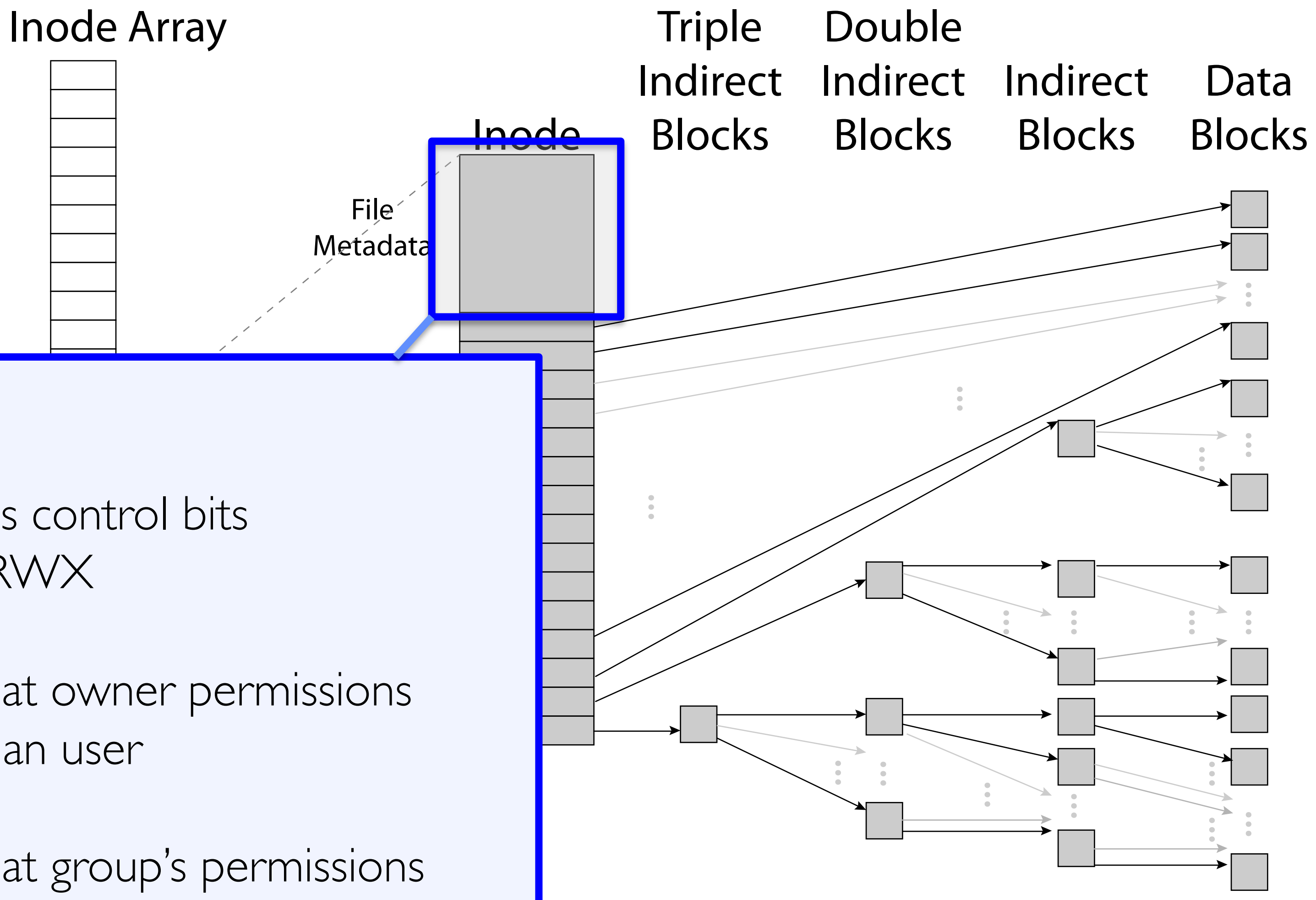
- Inode maintains a multi-level tree structure to find storage blocks for files
  - Great for little and large files
  - Asymmetric tree with fixed sized blocks

- Original ***inode*** format appeared in BSD 4.1 (more following)
  - Berkeley Standard Distribution Unix!
  - Similar structure for Linux Ext 2/3

Inode Structure



File Atributes

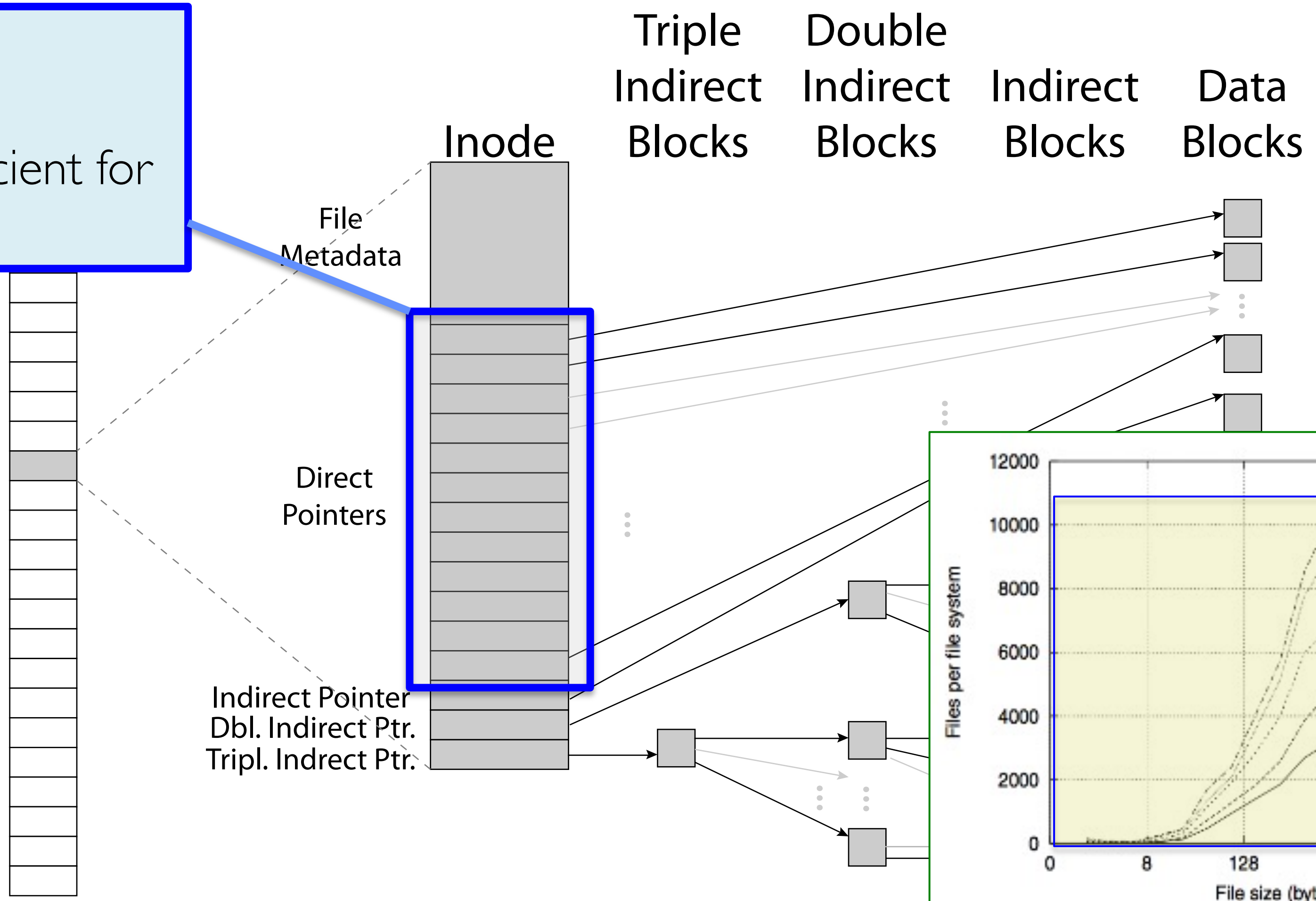


User
Group
9 basic access control bits
- UGO x RWX
SetUID bit
- execute at owner permissions rather than user
SetGID bit
- execute at group's permissions

Small Files: 12 Pointers Direct to Data Blocks

Direct pointers

4KB blocks ⇒ sufficient for files up to 48KB



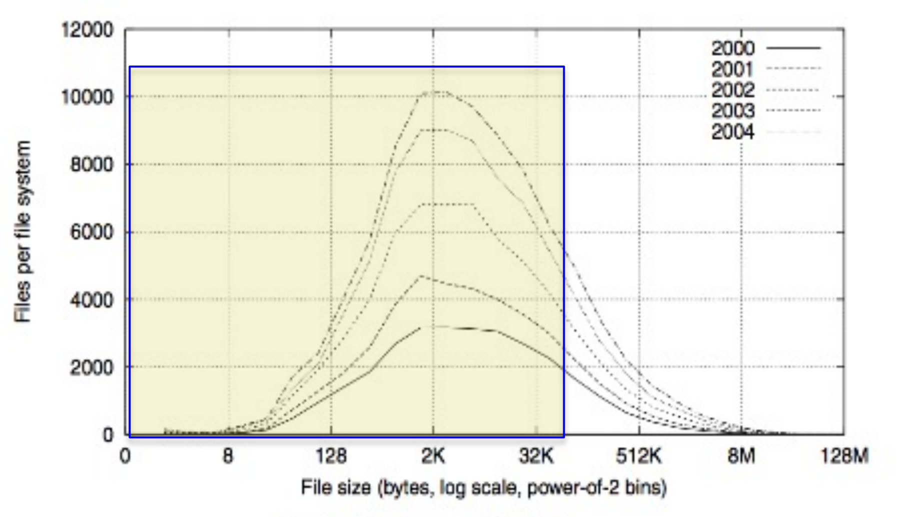


Fig. 2. Histograms of files by size.

Large Files: 1-, 2-, 3-level indirect pointers

Indirect pointers
- point to a disk block containing only pointers
- 4 KB blocks => 1024 ptrs
  => 4 MB @ level 2
  => 4 GB @ level 3
  => 4 TB @ level 4

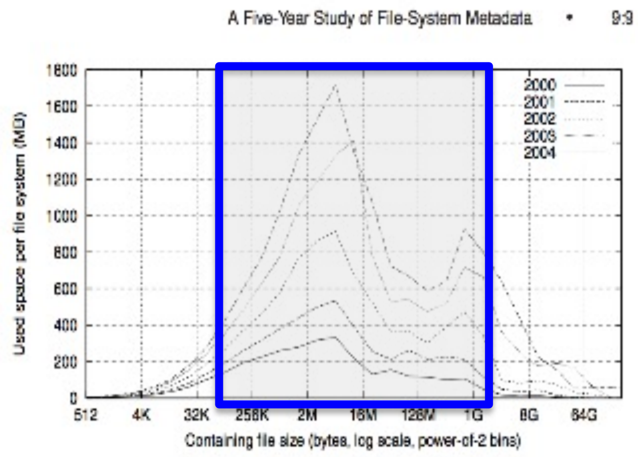
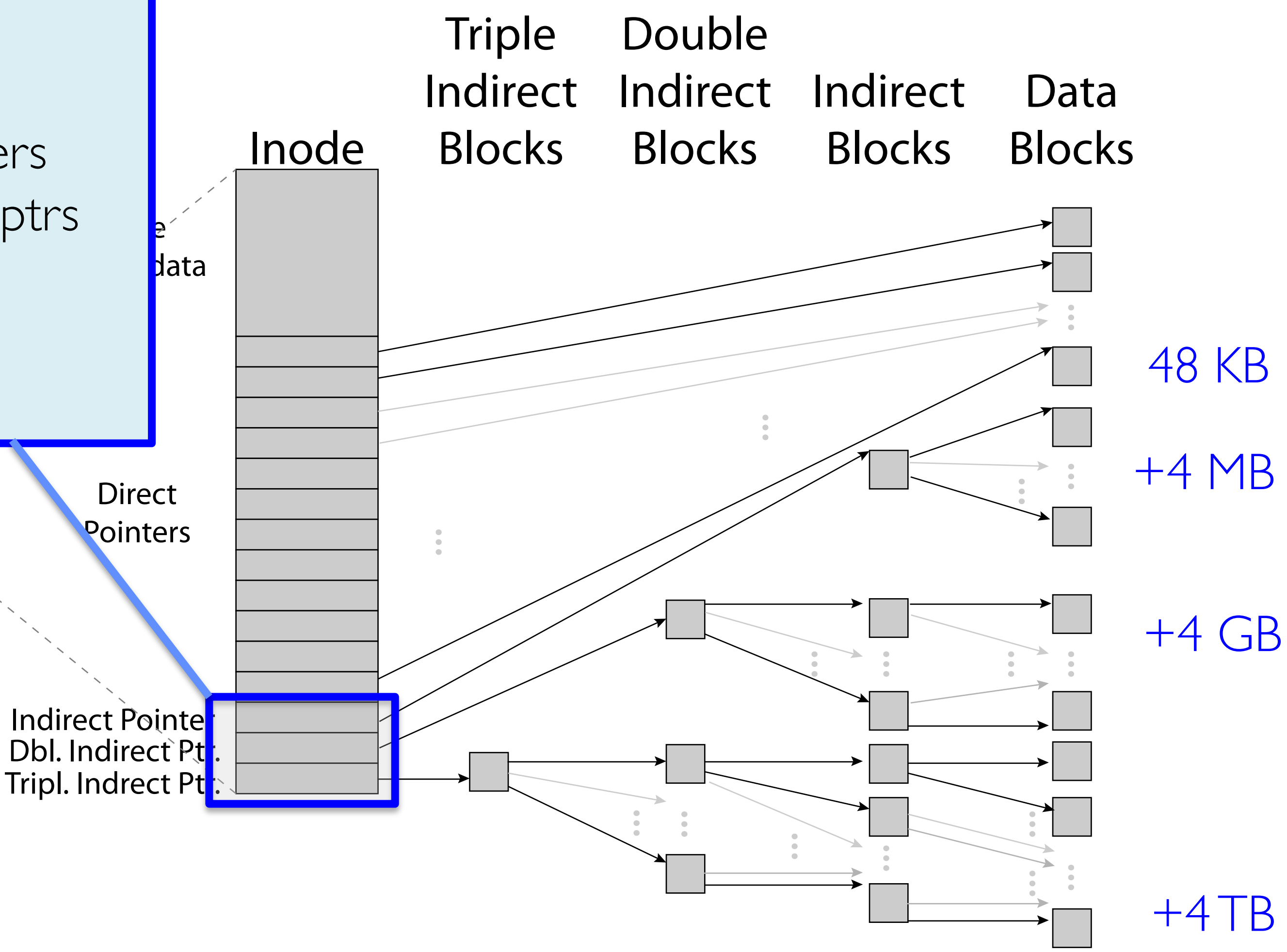
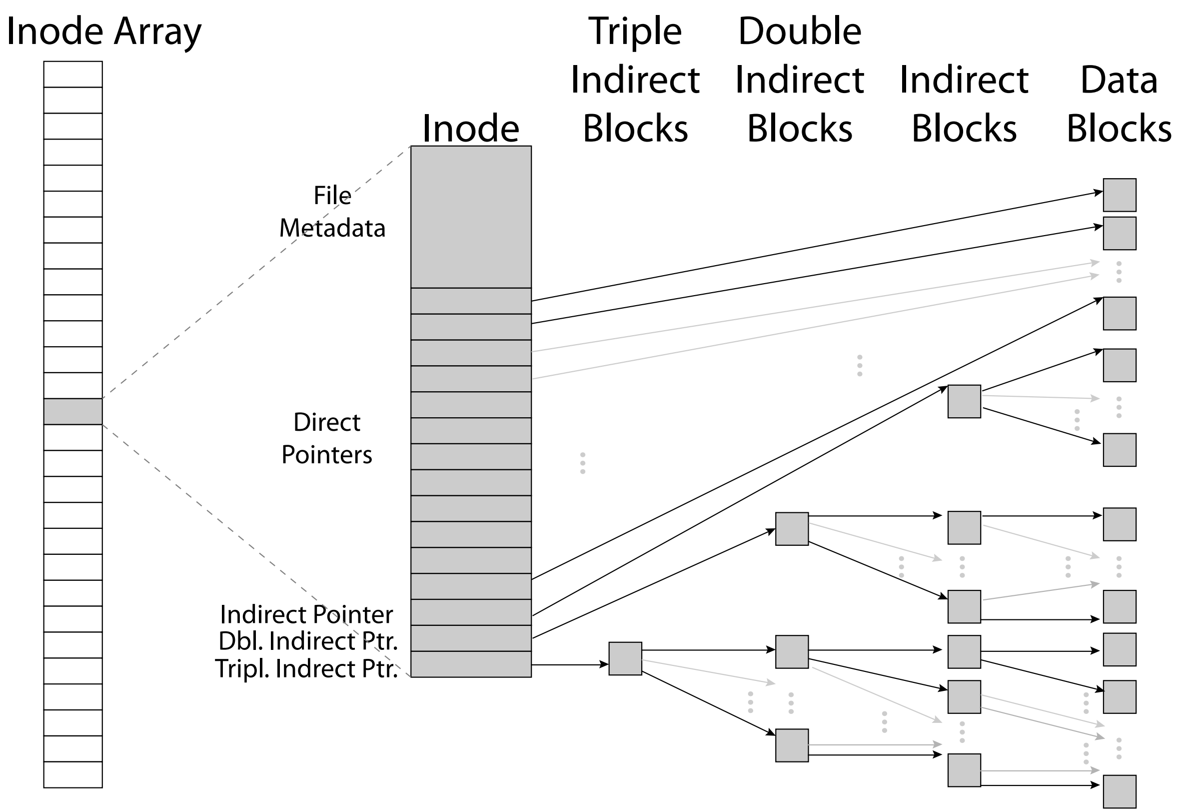


Fig. 4. Histograms of bytes by containing file size.



Putting it All Together: On-Disk Index

- Sample file in multilevel indexed format:
  - 10 direct ptrs, 1KB blocks
    - » 256 indirect blocks
    - » 256^2 double indirect blocks
    - » 256^3 triple indirect 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



CASE STUDY:
BERKELEY FAST FILE SYSTEM (FFS)

Fast File System (BSD 4.2, 1984)

- Same inode structure as in BSD 4.1
  - Same file header and triply indirect blocks like we just studied
  - Some changes to block sizes from 1024 $\Rightarrow$ 4096 bytes for performance
- Paper on FFS: "A Fast File System for UNIX"
  - Marshall McKusick, William Joy, Samuel Leffler and Robert Fabry

- Optimization for Performance and Reliability:
  - Distribute inodes among different tracks to be closer to data
  - Use bitmap allocation in place of freelist
  - Attempt to allocate files contiguously
  - 10% reserved disk space
  - Skip-sector positioning

FFS Changes in Inode Placement: Motivation

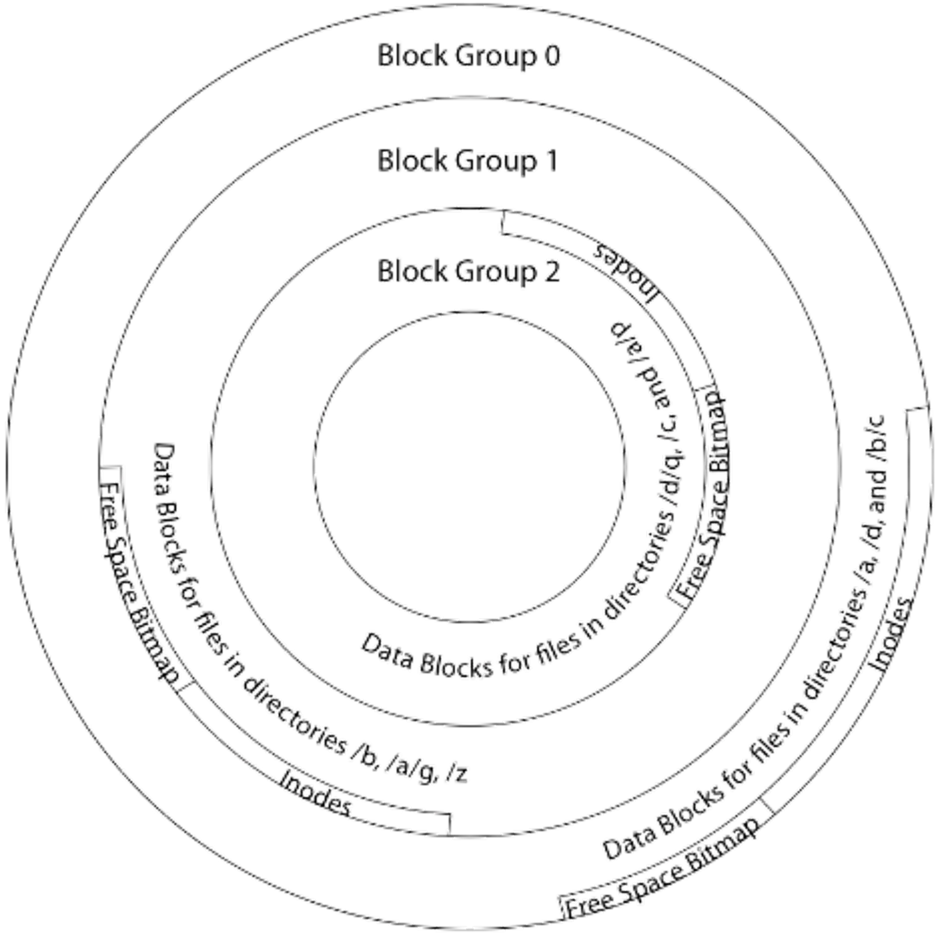
- In early UNIX and DOS/Windows FAT file system, headers stored in special array in outermost cylinders
  - Fixed size, set when disk is formatted
    - » At formatting time, a fixed number of inodes are created
    - » Each is given a unique number, called an "inumber"

- 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 they point to
    - » To read a small file, seek to get header, seek to get 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

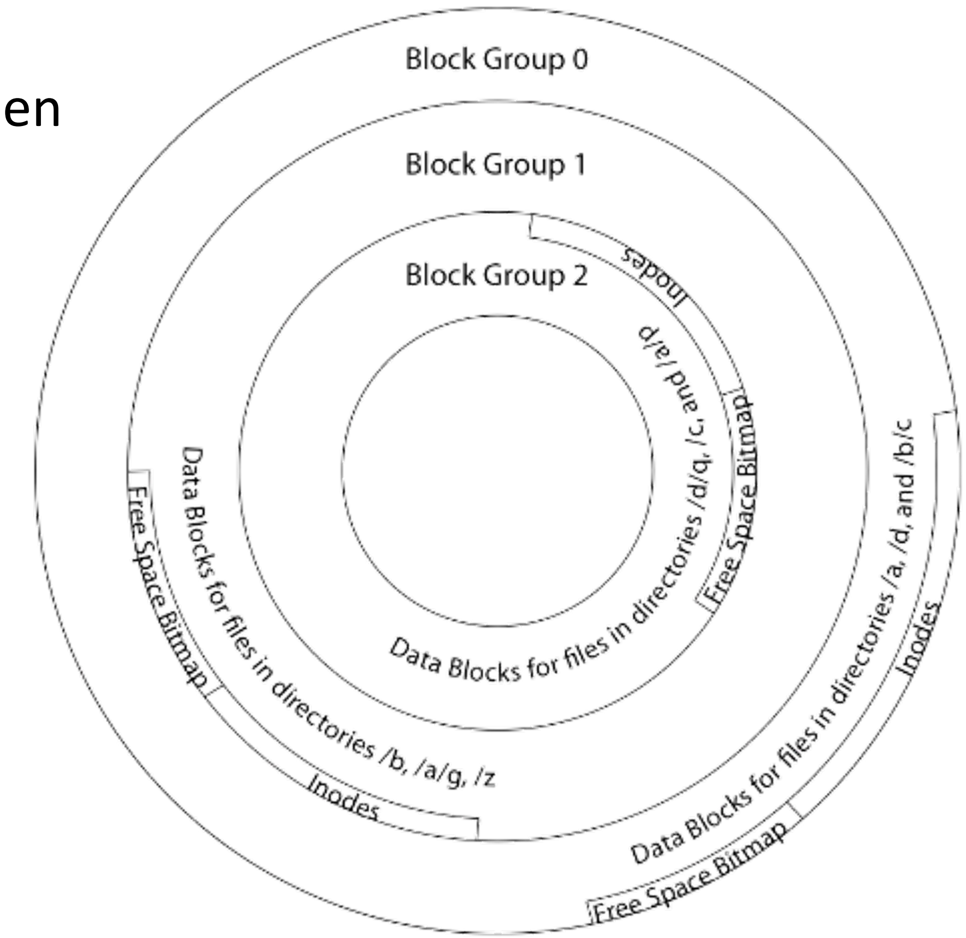
FFS Locality: Block Groups

- 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

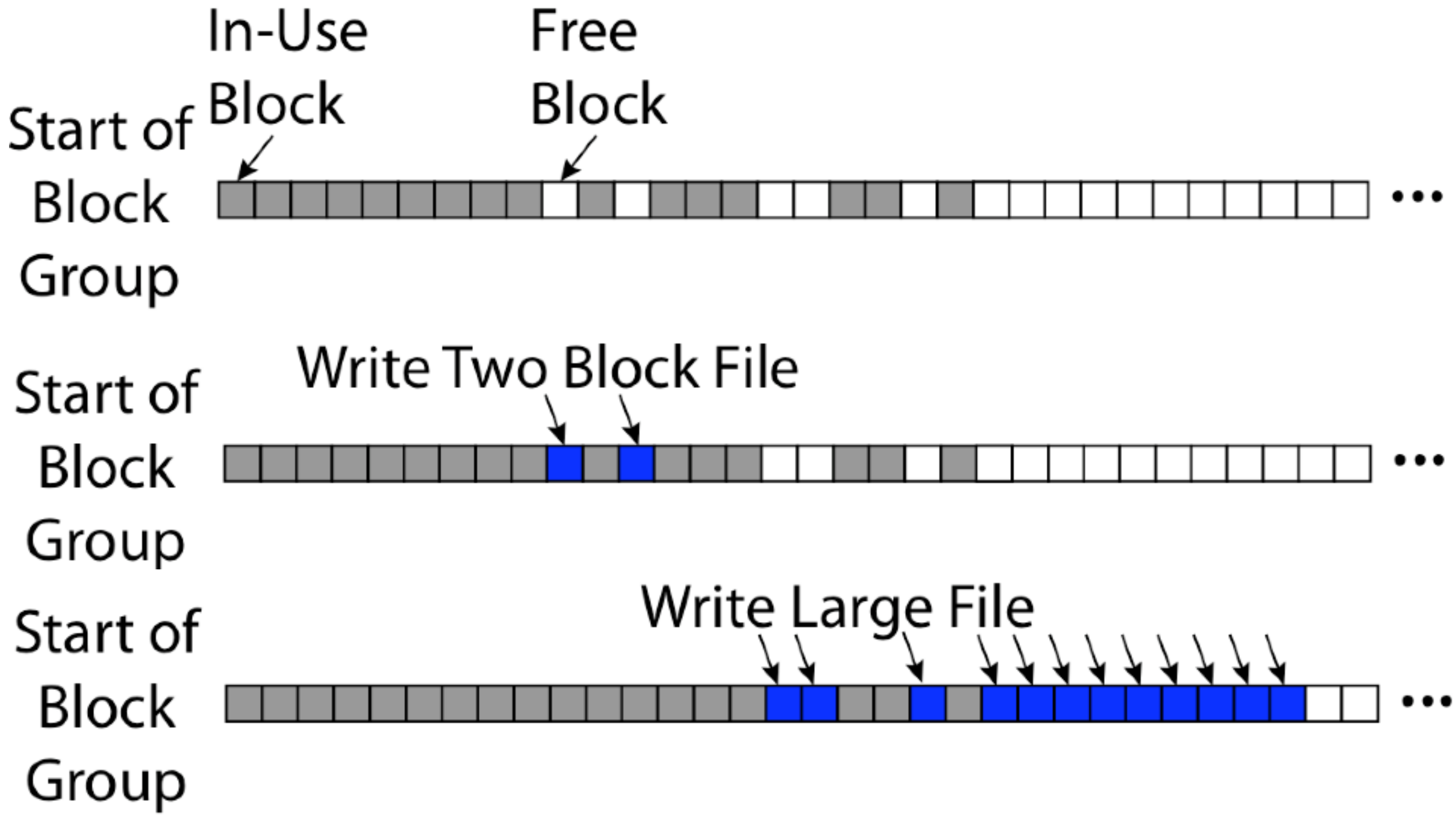


FFS Locality: Block Groups (Con't)

- 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 $\Rightarrow$ 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)

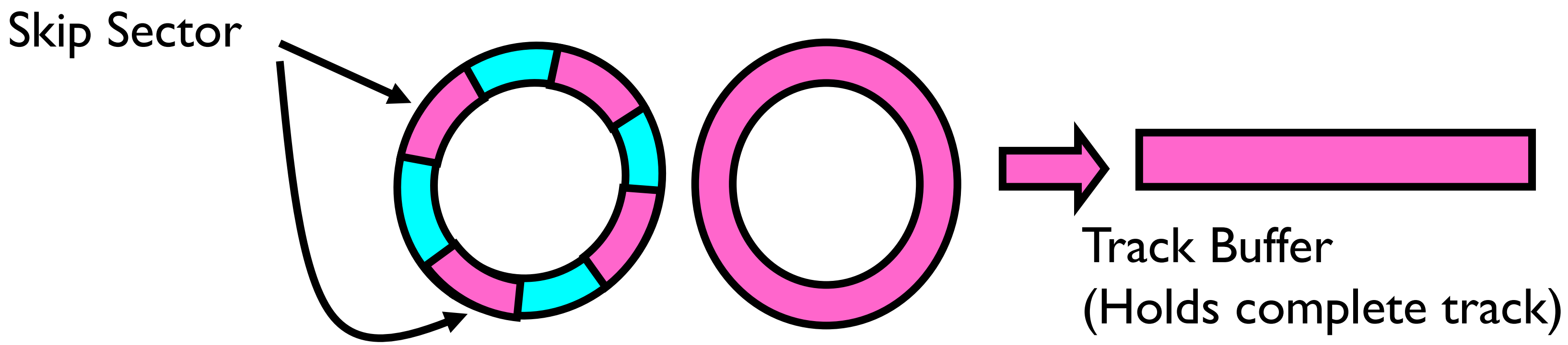


UNIX 4.2 BSD FFS First Fit Block Allocation



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

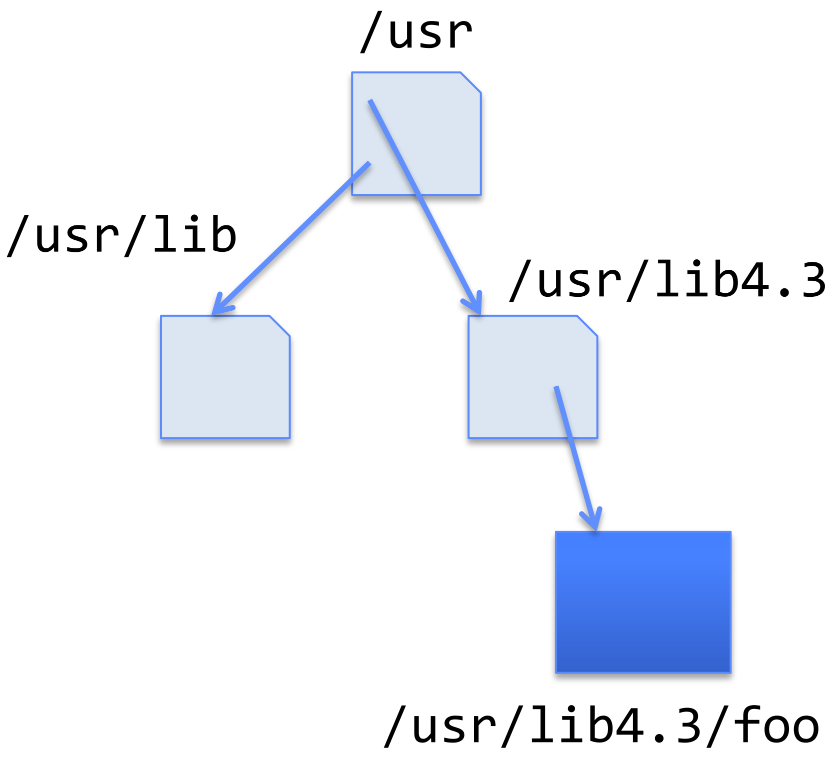
UNIX 4.2 BSD FFS

- 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

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

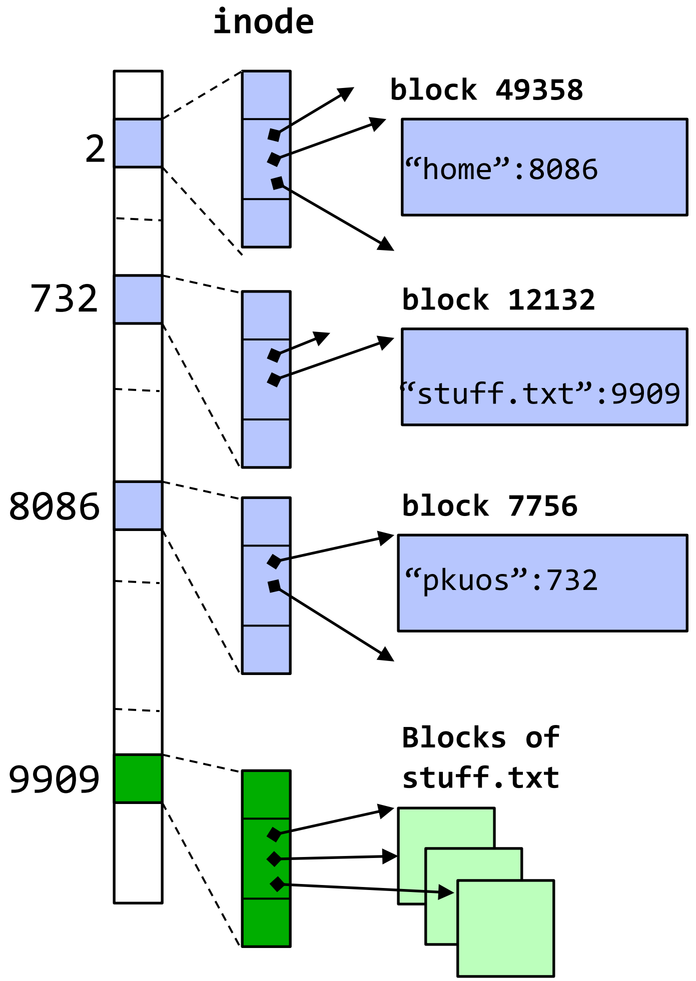
- Contrast these two different types of directory entries:
  - Normal directory entry: <file name, file #>
  - Symbolic link: <file name, dest. file name>

- 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/pkuos/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 "pkuos" to get its inumber (say 732)
- Read inode 732 for /home/pkuos, extract its blocks, read block (say 12132), scan it for "stuff.txt" to get its inumber, say 9909
- Read inode 9909 for /home/pkuos/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

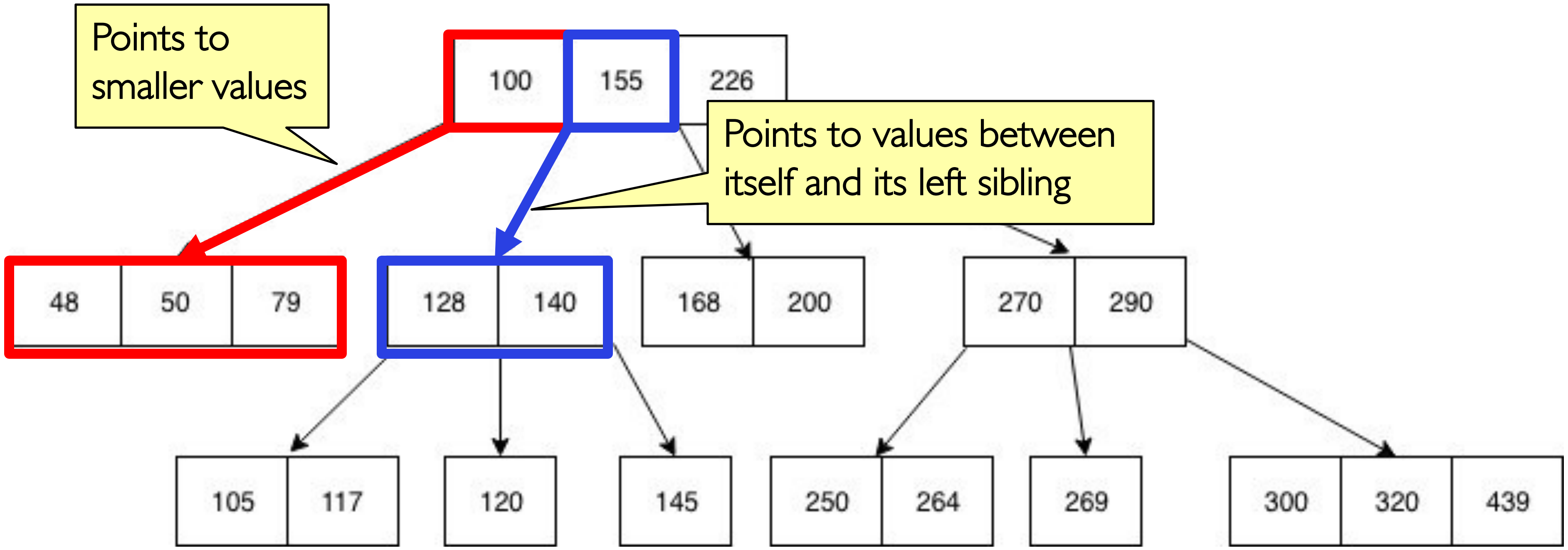
- Early file systems organize directories as:
  - List of <file_name, inode> entries
  - Array of <file_name, inode> entries

- Challenges
  - Linear search: expensive
  - Might need to read entire directory just to find a file: many disk accesses

Large Directories: B-Trees (dirhash)

in FreeBSD, NetBSD, OpenBSD

Recall B-Trees data structure



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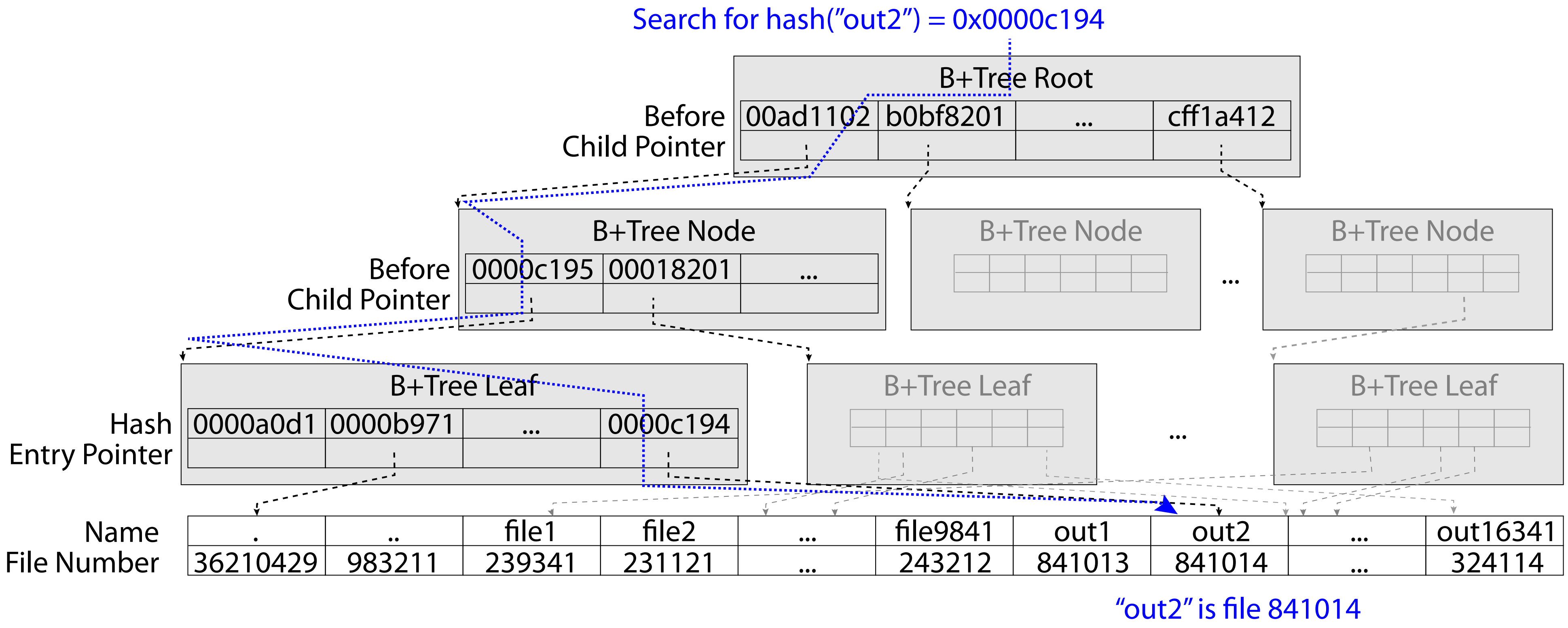
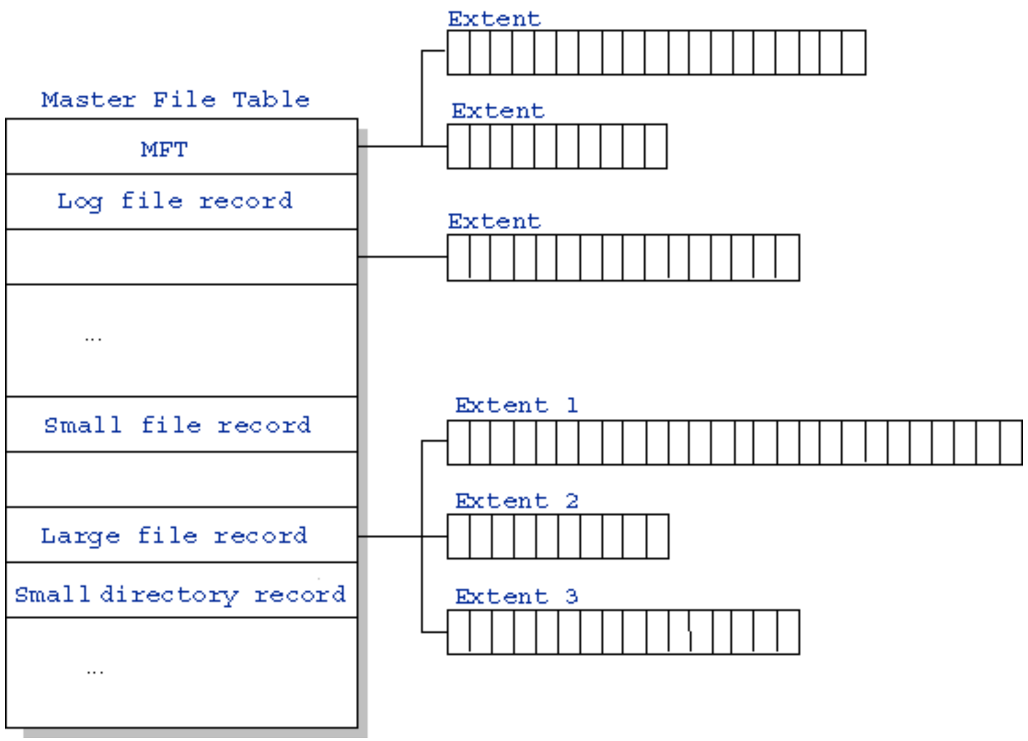


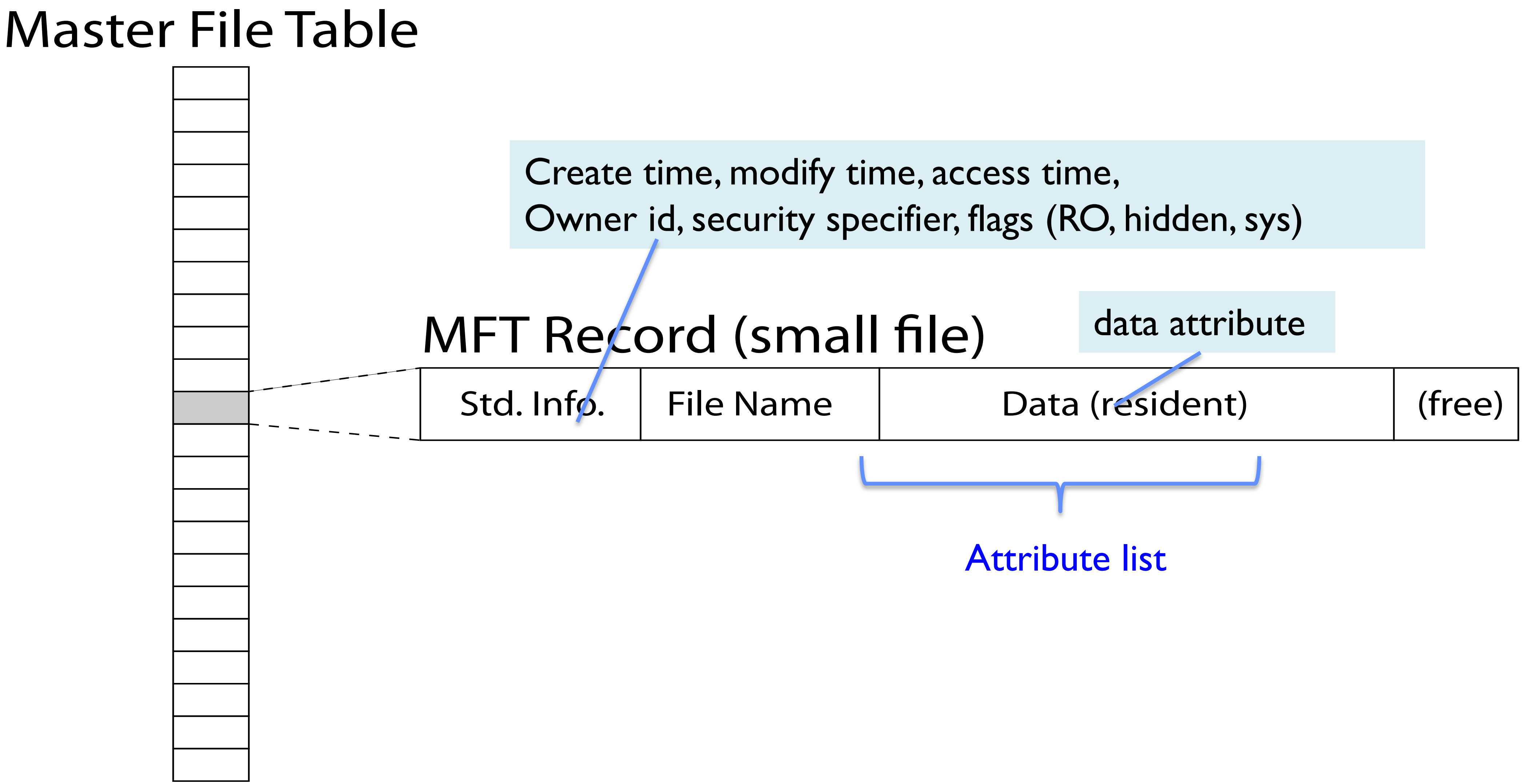
CASE STUDY:
WINDOWS NTFS

New Technology File System (NTFS)

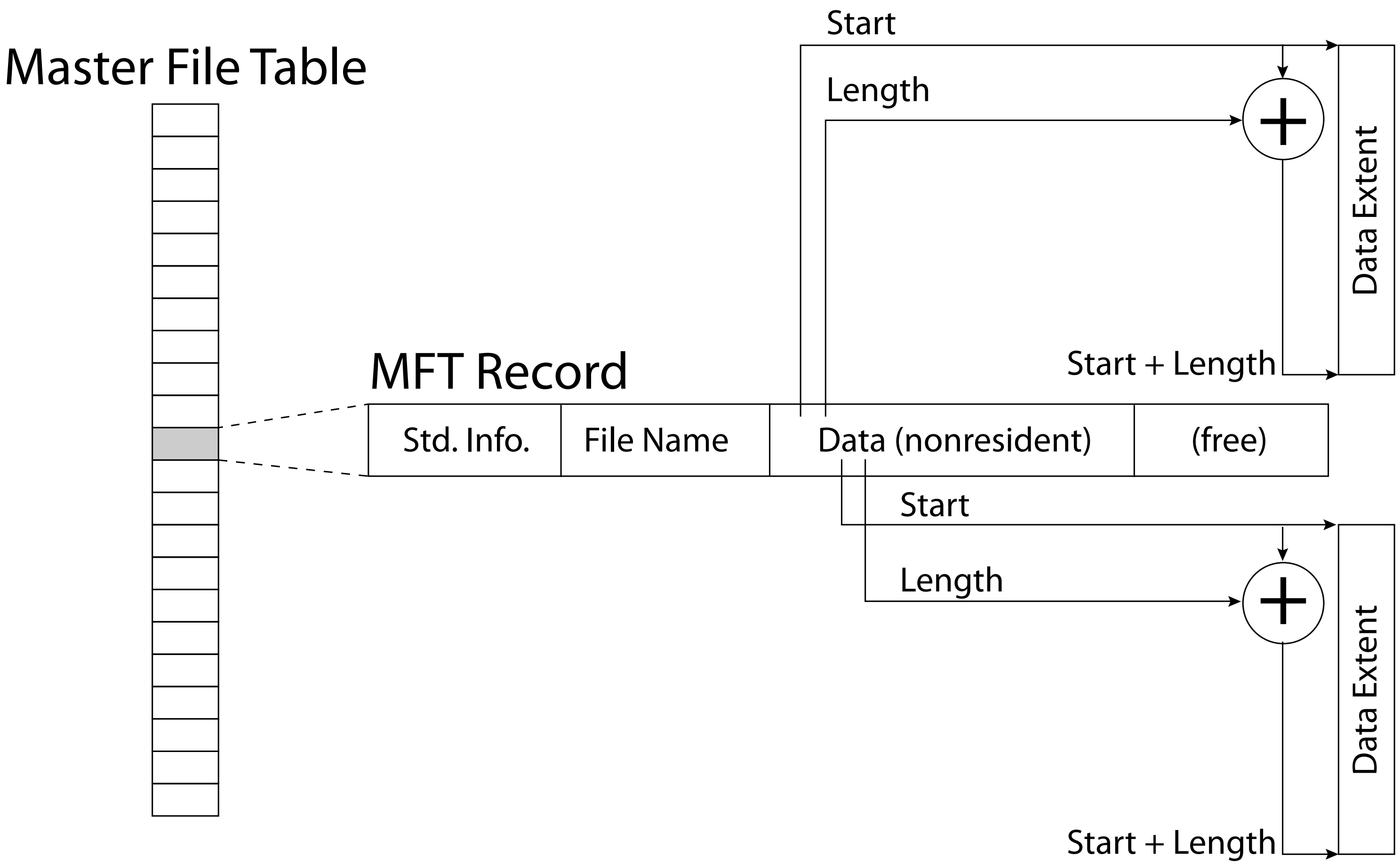
- Default on modern Windows systems
- Variable length extents
  - Rather than fixed blocks
- Instead of FAT or inode array: Master File Table
  - Like a database, with max 1 KB size for each table entry
  - Everything (almost) is a sequence of <attribute:value> pairs
    - » Meta-data and data
- Each 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



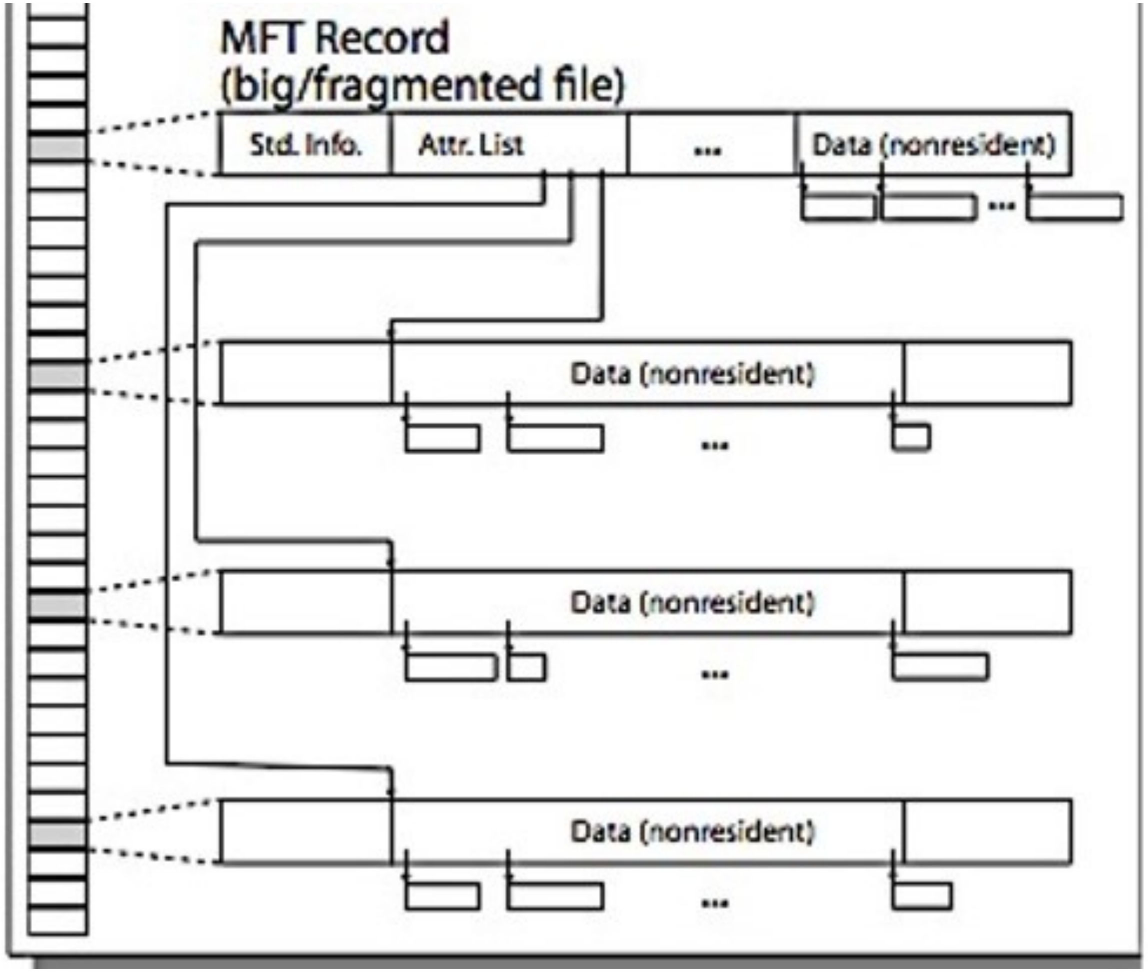
NTFS Small File: Data stored with Metadata



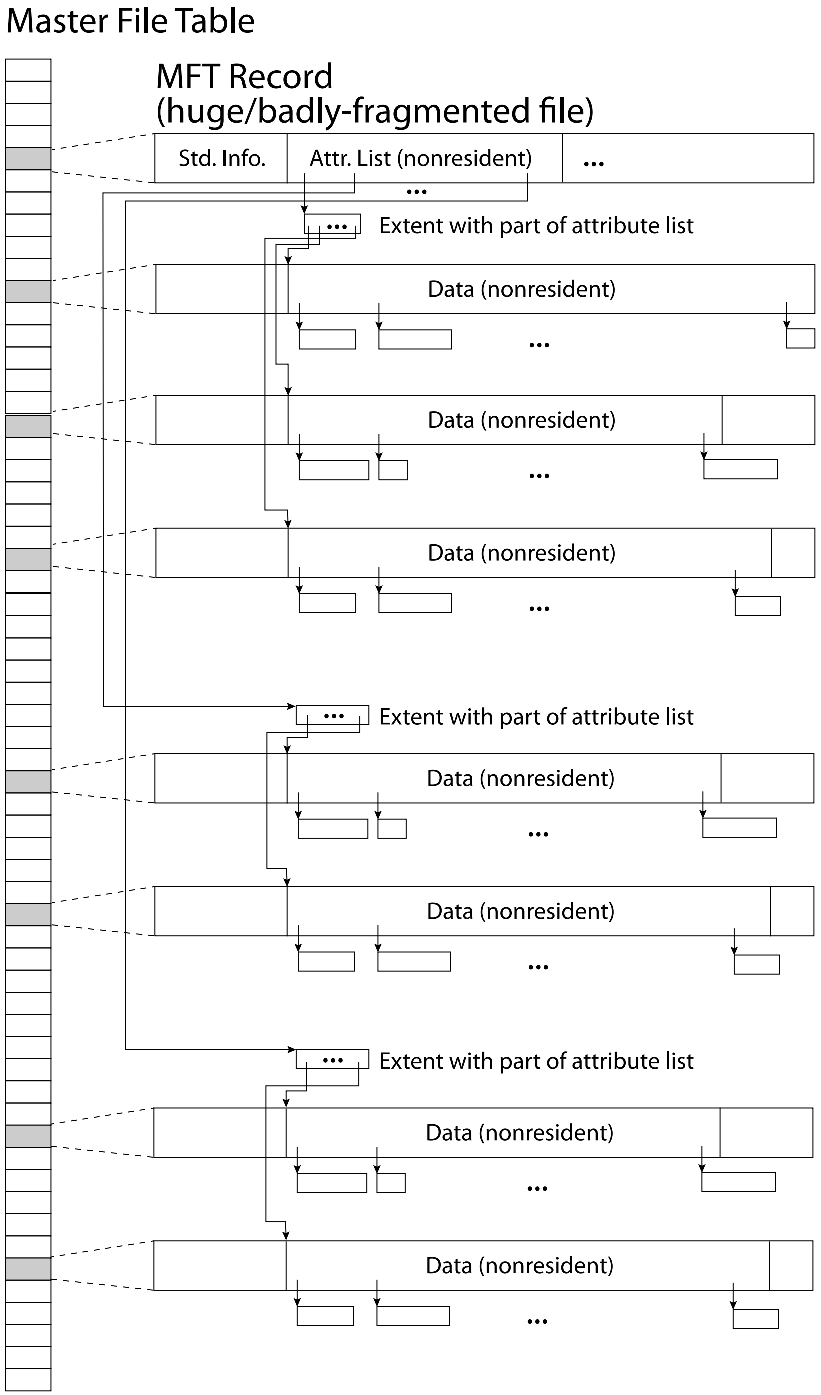
NTFS Medium File: Extents for File Data



NTFS Large File: Pointers to Other MFT Records



NTFS Huge, Fragmented File: Many MFT Records



NTFS Directories

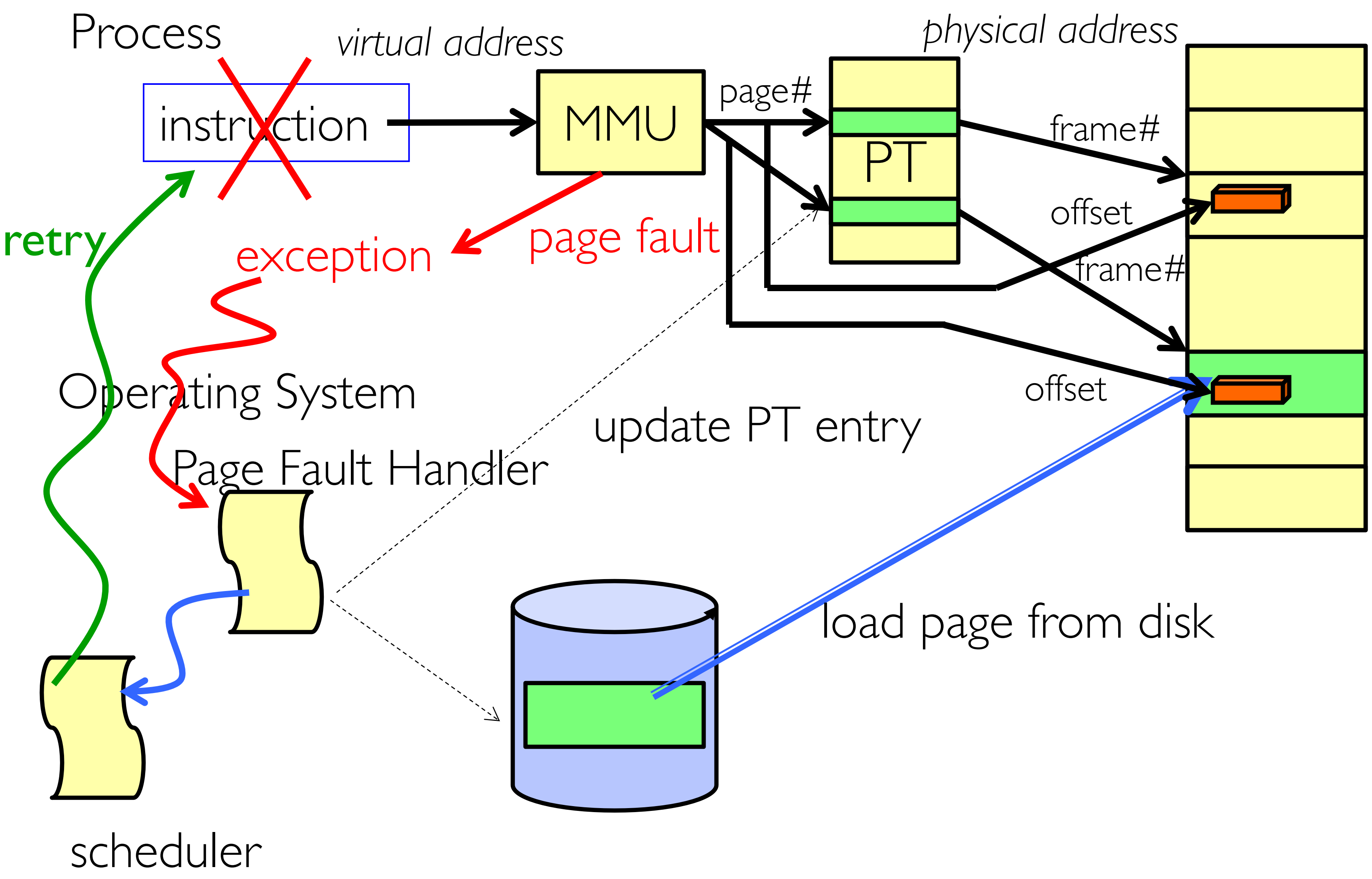
- Directories implemented as B Trees
- File's number identifies its entry in MFT
- MFT entry always has a file name attribute
  - Human readable name, file number of parent dir
- Hard link? Multiple file name attributes in MFT entry

MEMORY MAPPED FILES

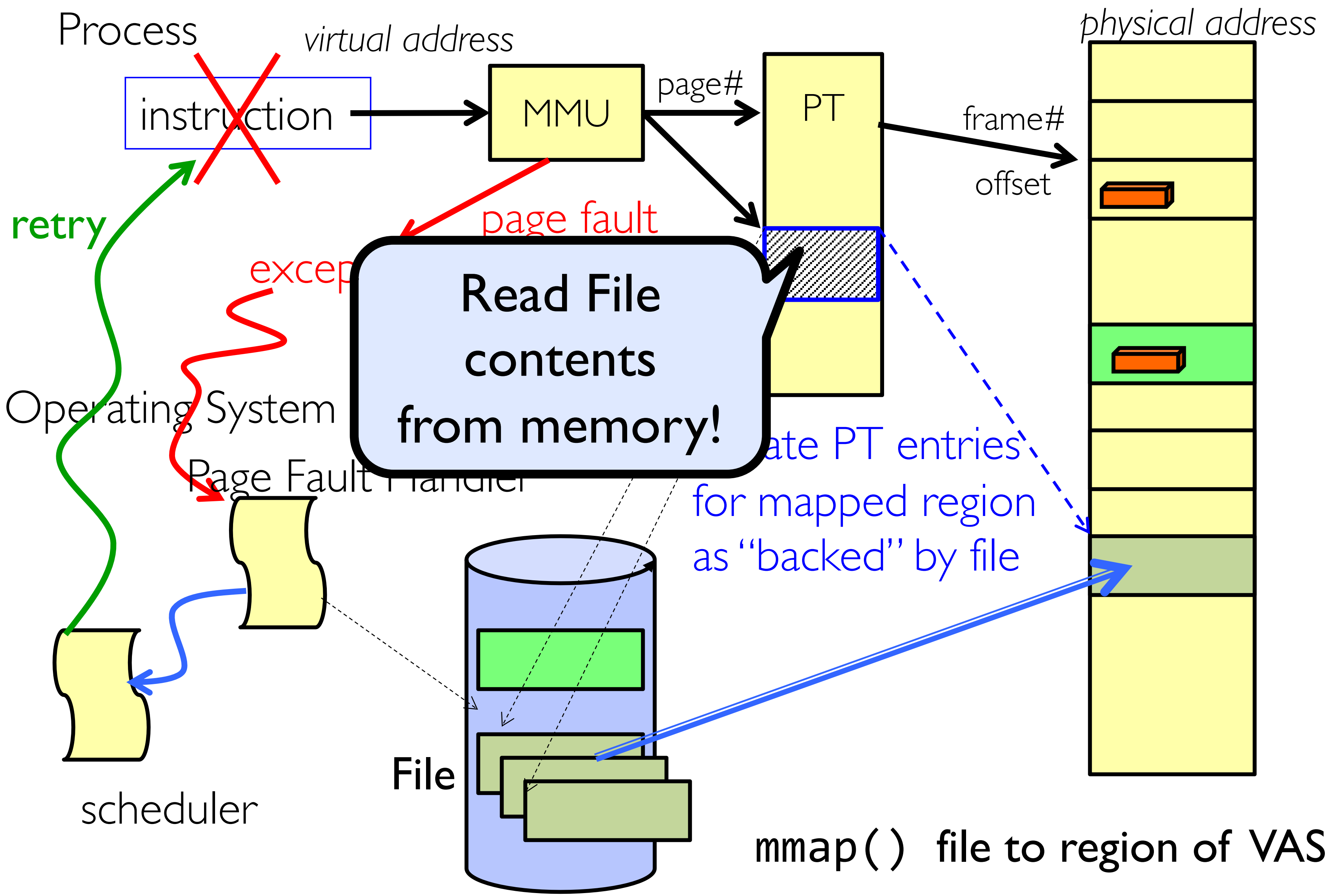
Memory Mapped Files

- Traditional I/O involves explicit transfers between buffers in process address space to/from regions of a file
  - This involves multiple copies into buffers 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
- Executable files are treated this way when we exec the process!!

Recall: Who Does What, When?



Using Paging to mmap() Files



mmap() file to region of VAS

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

```c
#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 unsigned int) &something);
  printf("Heap at : %16lx\n", (long unsigned int) malloc(1));
  printf("Stack at: %16lx\n", (long unsigned int) &mfile);

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

  /* map the file */
  mfile = mmap(0, 10000, PROT_READ|PROT_WRITE, MAP_FILE|MAP_SHARED, myfd, 0);
  if (mfile == MAP_FAILED) {perror("mmap failed"); exit(1);}

  ma                           (long unsigned int) mfile);

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

Return starting address

OS chooses starting address

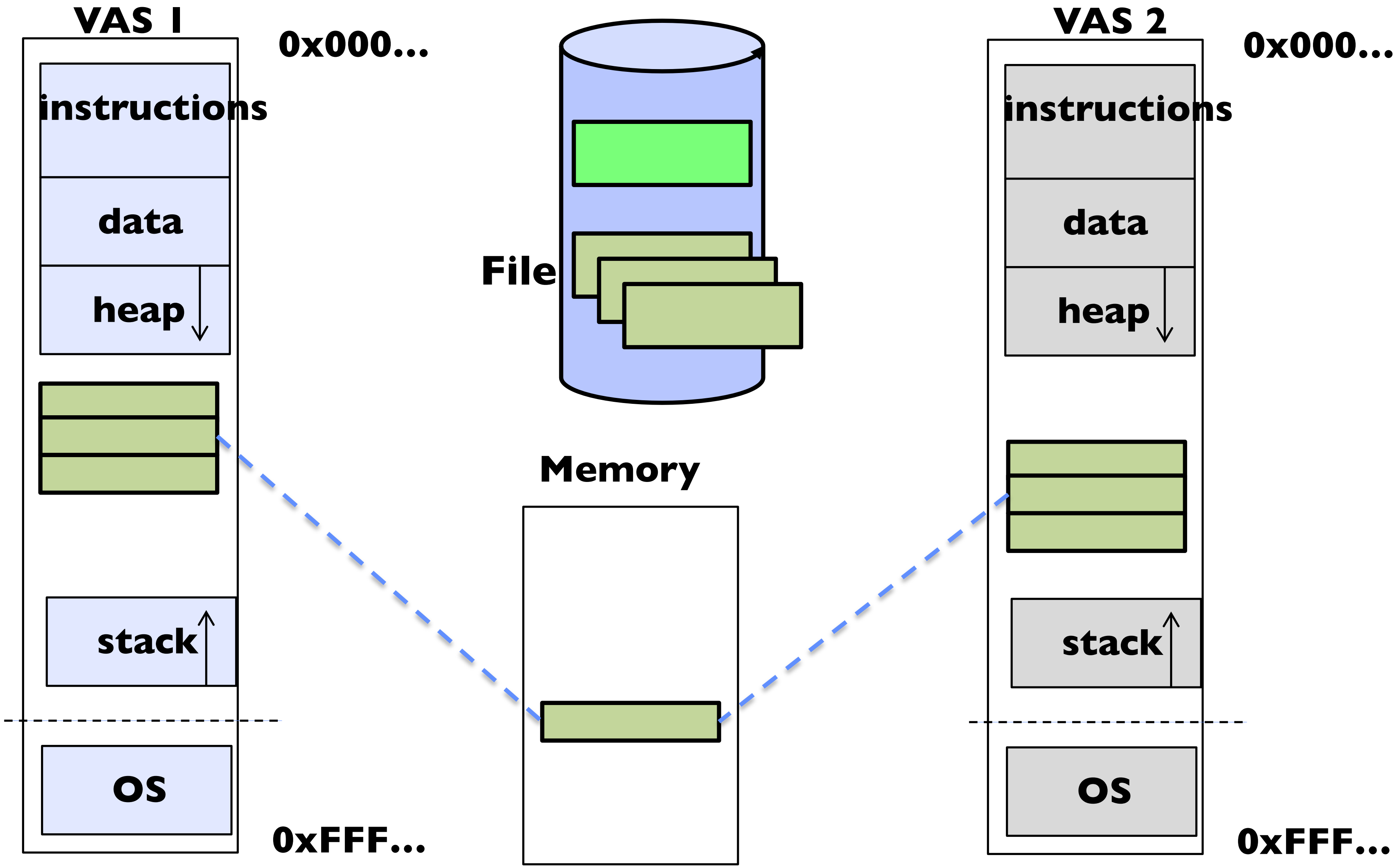
An mmap() Example

```
#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

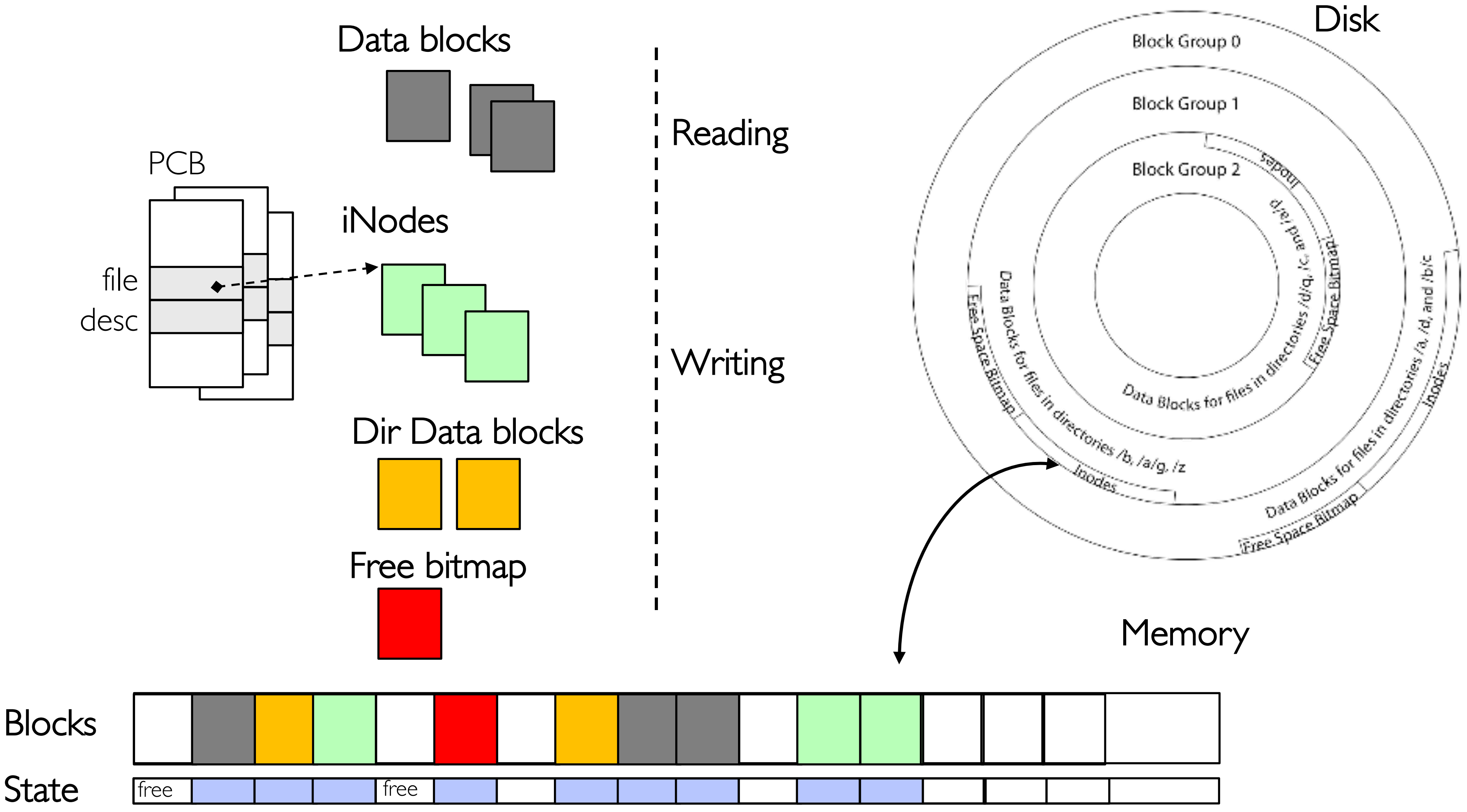
THE BUFFER CACHE

Buffer Cache

- Kernel *must* copy disk blocks to main memory to access their contents and write them back if modified
  - Could be data blocks, inodes, directory contents, etc.
  - Possibly dirty (modified and not written back)
- Key Idea: Exploit locality by caching disk data in memory
  - Name translations: mapping from paths $\rightarrow$ inodes
  - Disk blocks: mapping from block address $\rightarrow$ 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)

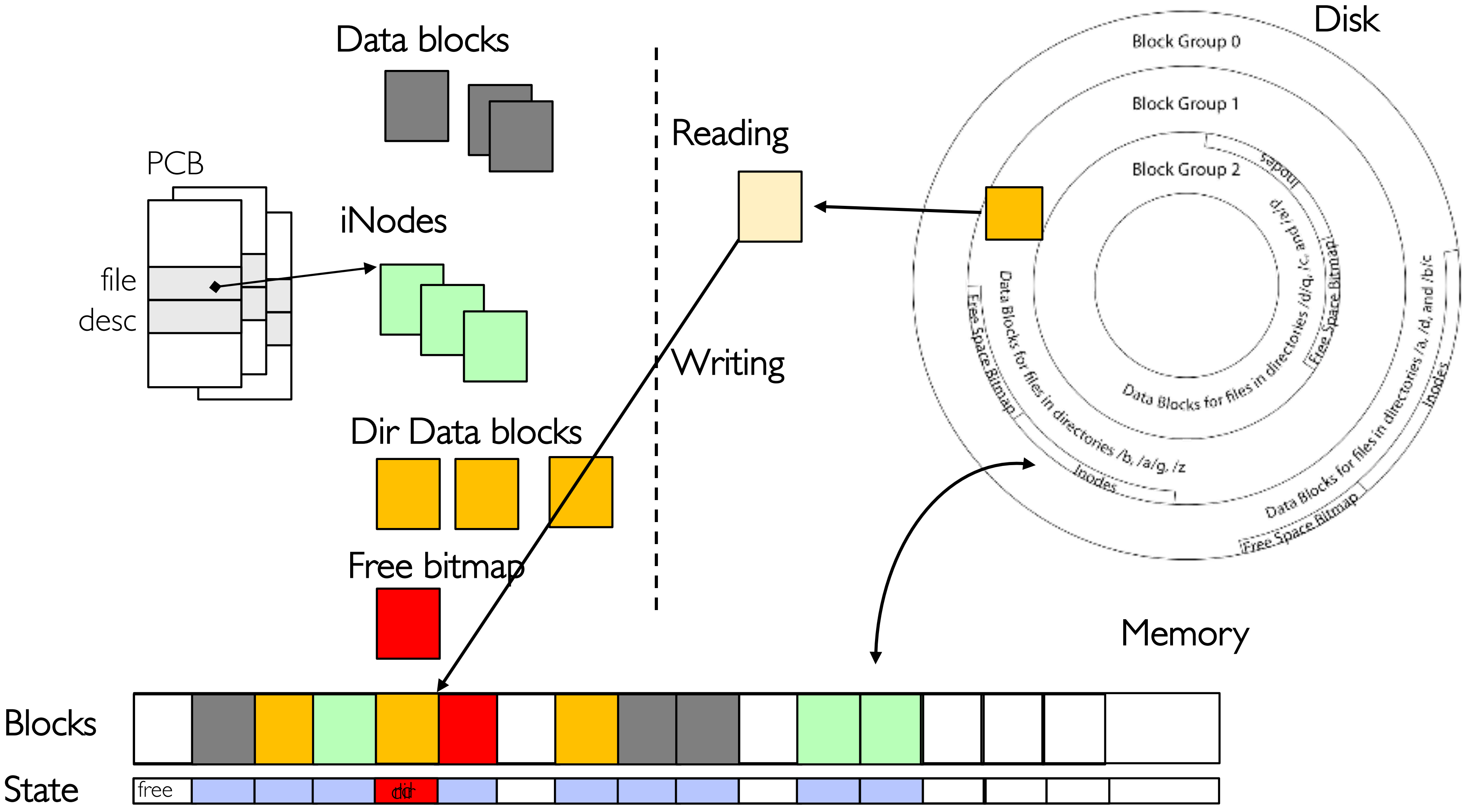
File System Buffer Cache

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



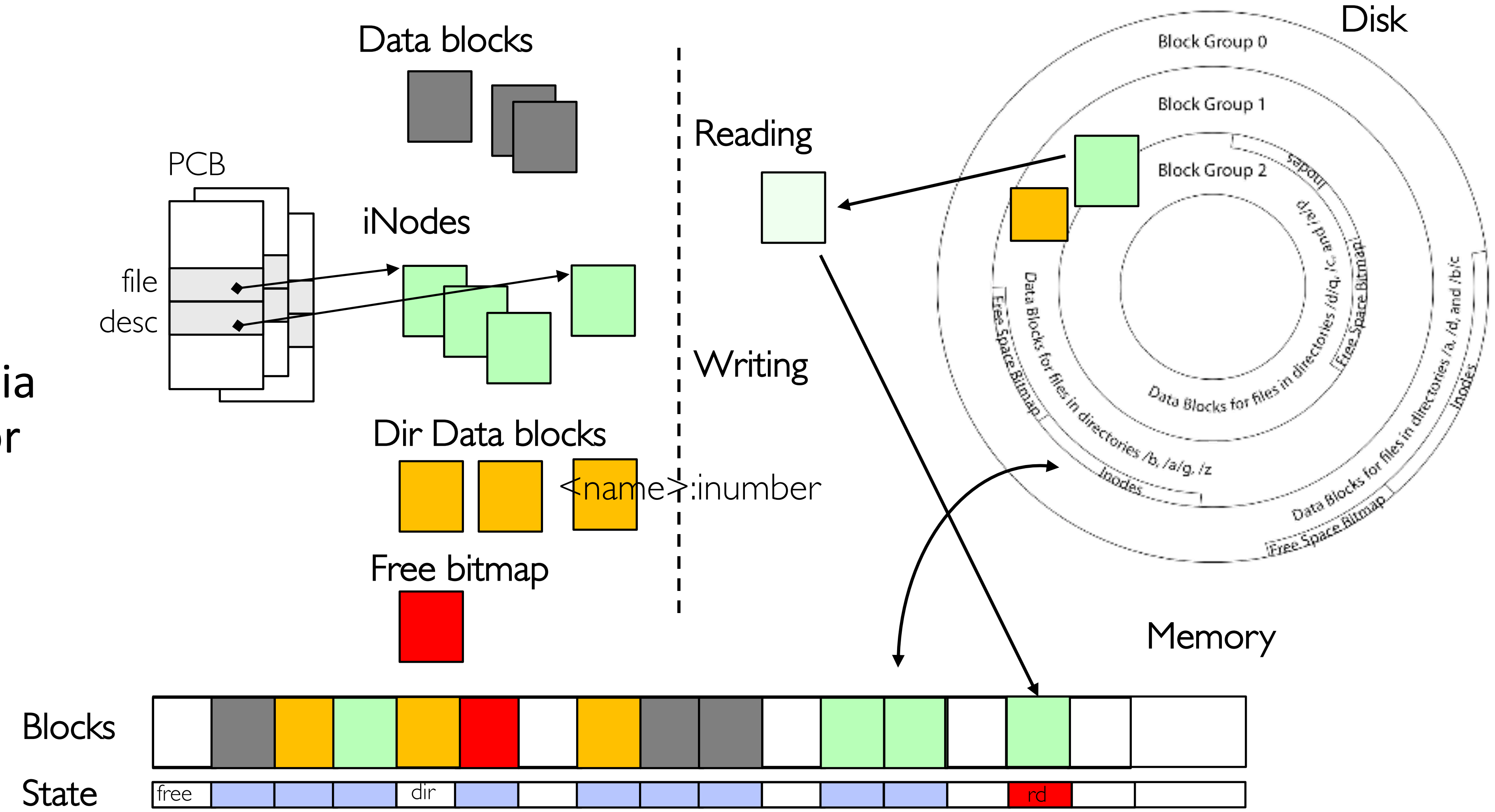
File System Buffer Cache: open

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



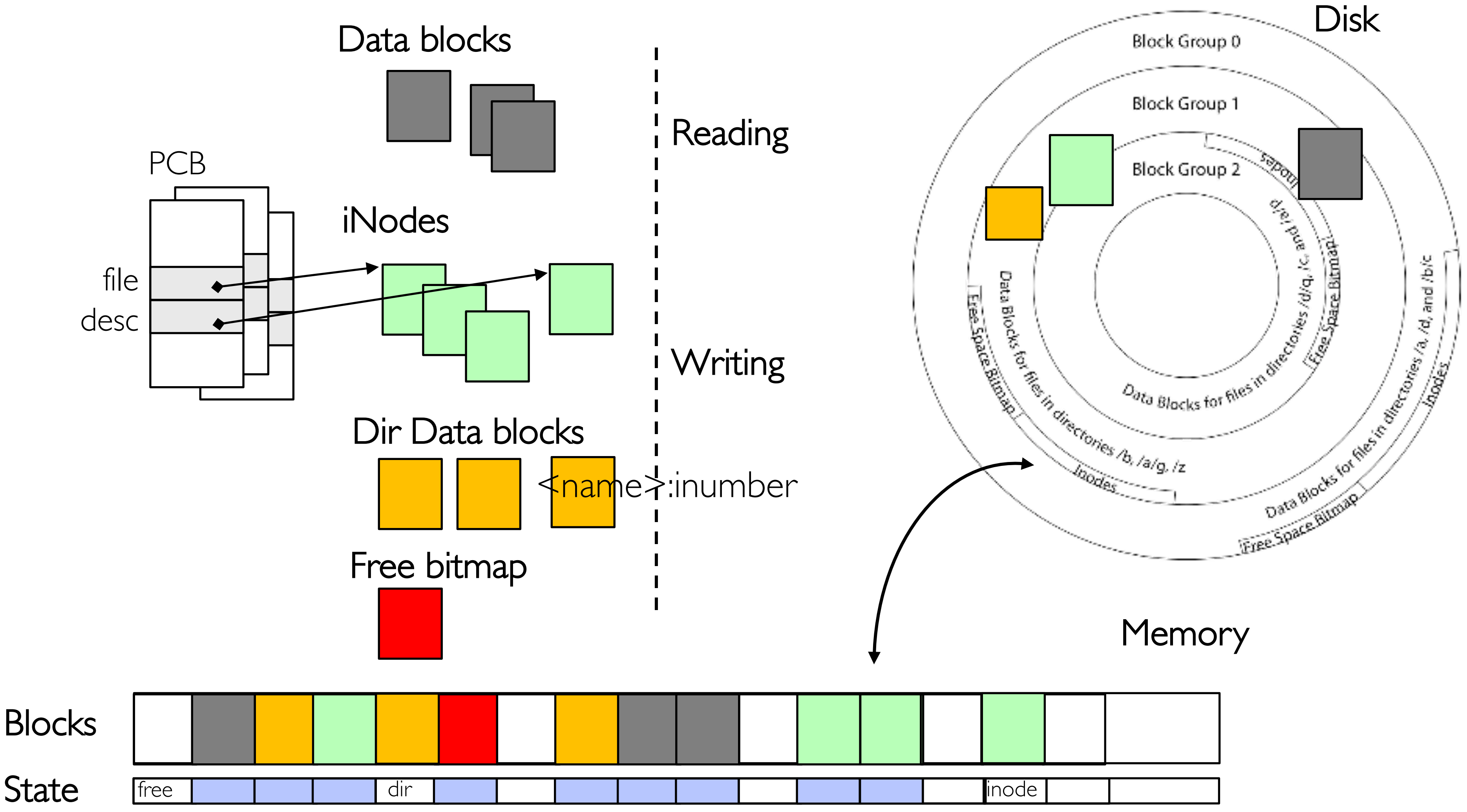
File System Buffer Cache: open

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



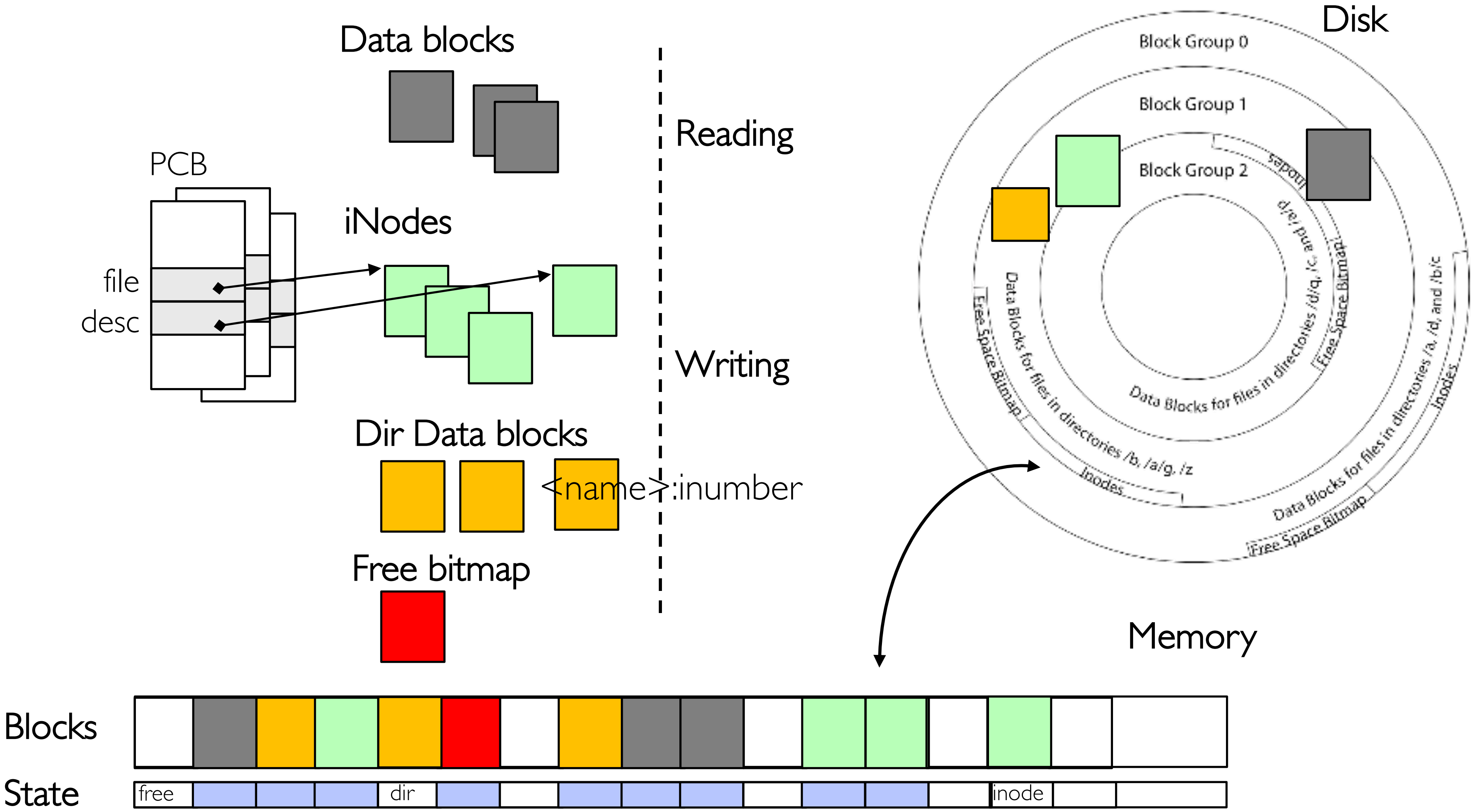
File System Buffer Cache: Read?

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



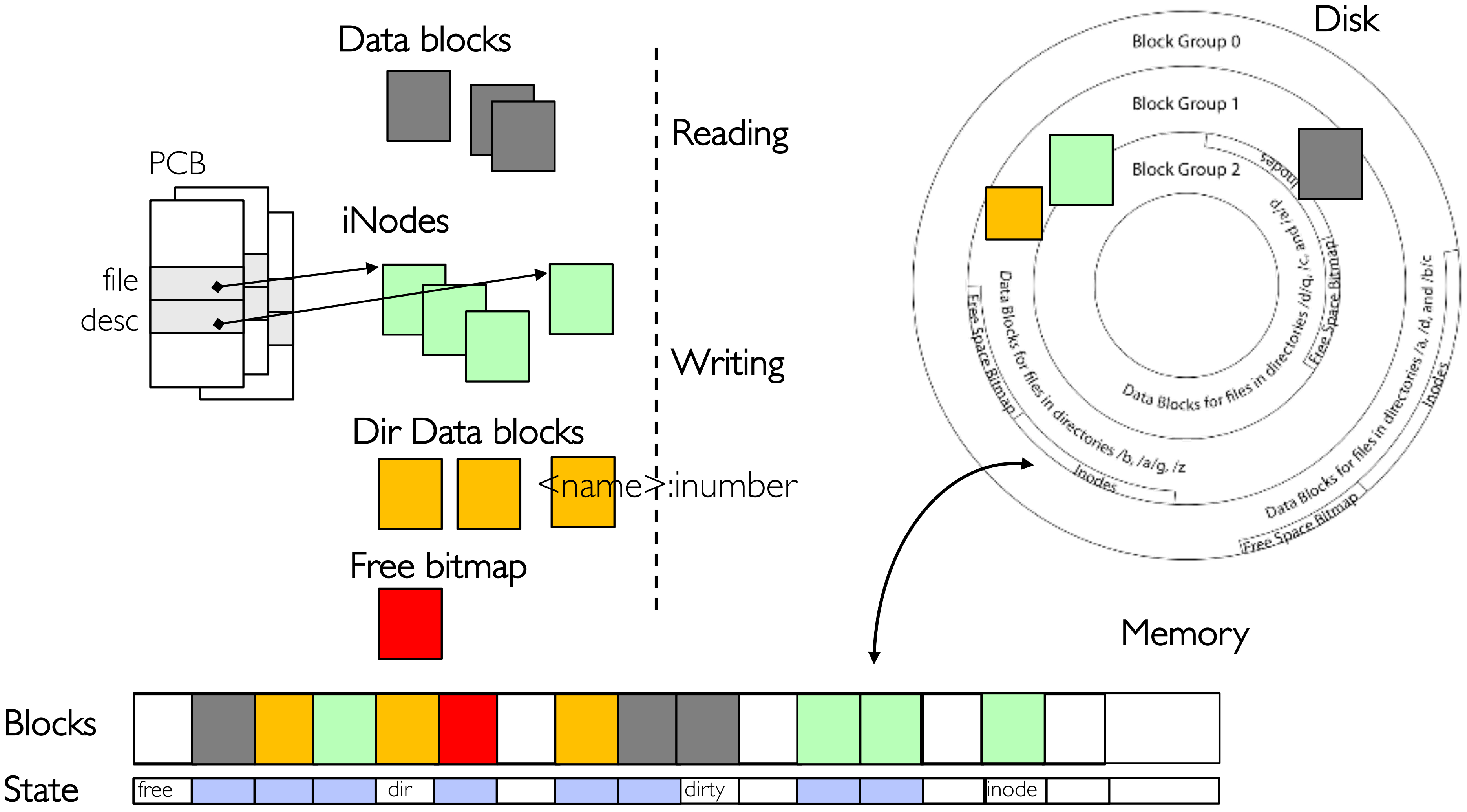
File System Buffer Cache: Write?

- 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
- 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 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)