CS162
Operating Systems and Systems Programming
Lecture 19

File Systems (Con't), MMAP

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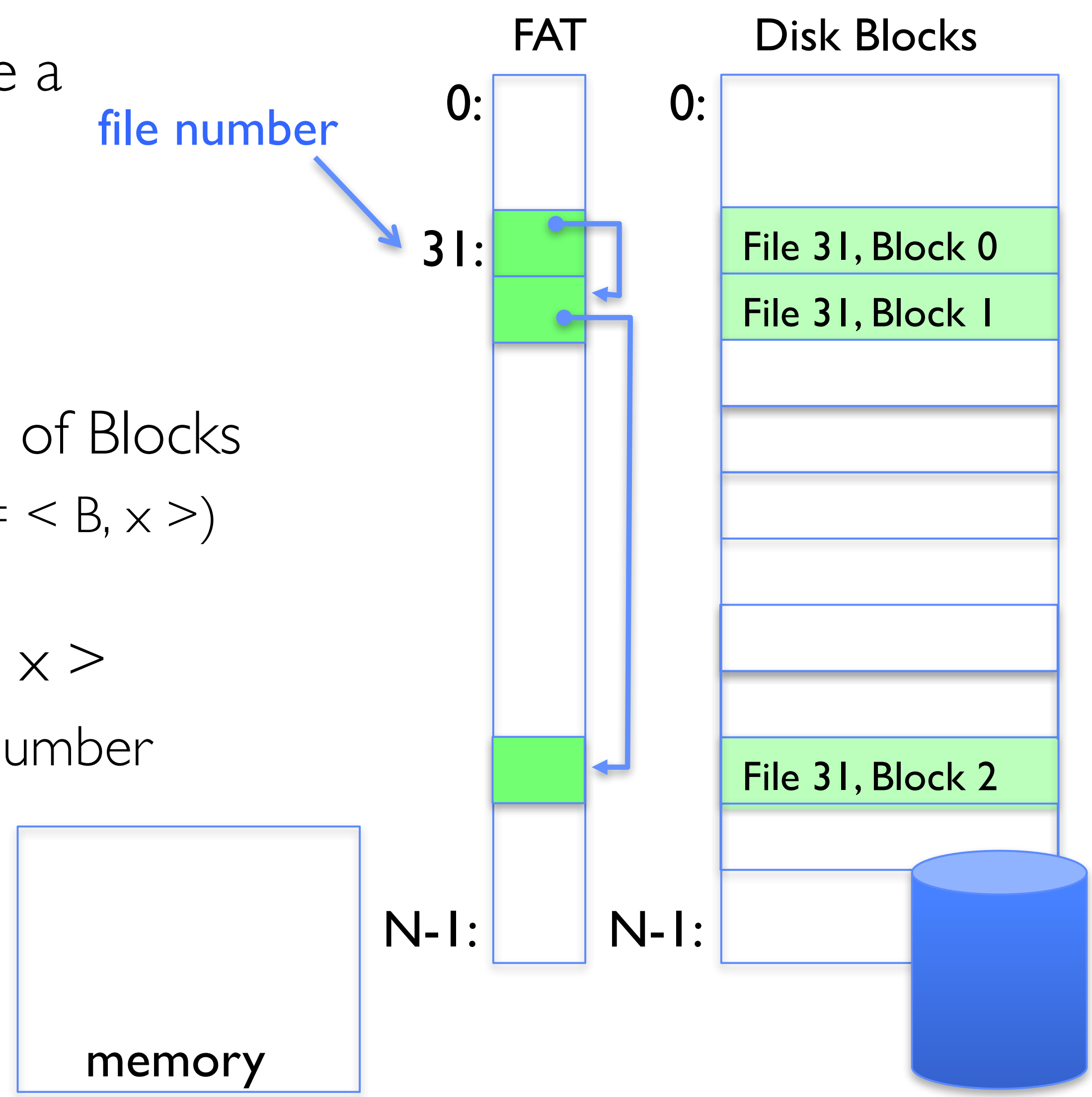
Our first filesystem: FAT (File Allocation Table)

- The most commonly used filesystem in the world!

- 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



Directory Structure (cont'd)

- 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")

Many Huge FAT Security Holes!

- FAT has no access rights
- FAT has no header in the file blocks
- Just gives an index into the FAT
  - (file number = block number)

Characteristics of Files

A Five-Year Study of File-System Metadata

NITIN AGRAWAL
University of Wisconsin, Madison
and
WILLIAM J. BOLOSKY, JOHN R. DOUCEUR, and JACOB R. LORCH
Microsoft Research

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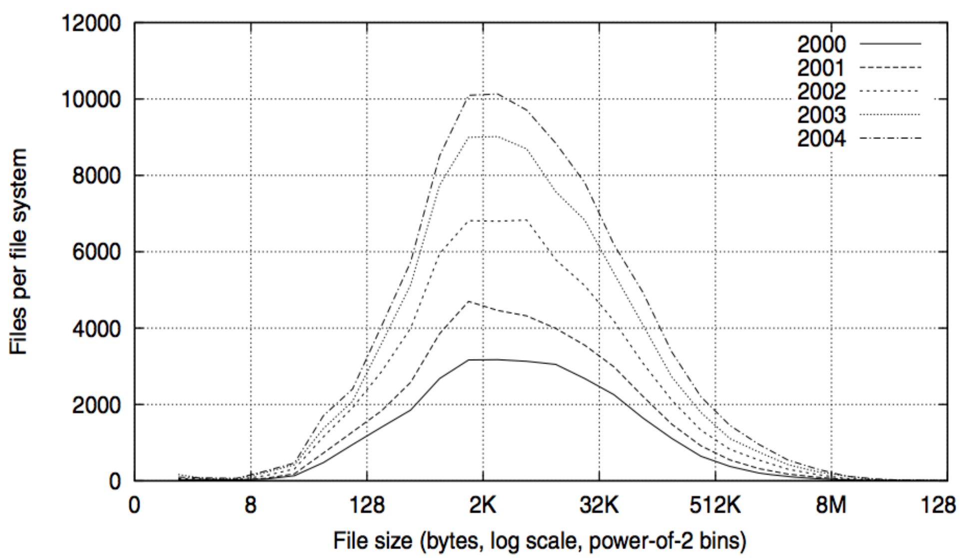


Fig. 2. Histograms of files by size.

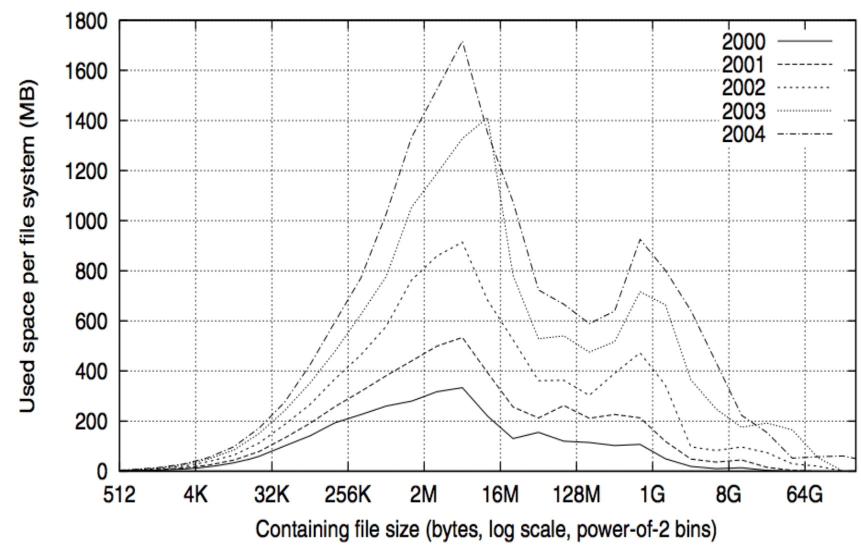


Fig. 4. Histograms of bytes by containing file size.

Characteristics of Files

- Most files are small, growing numbers of files over time

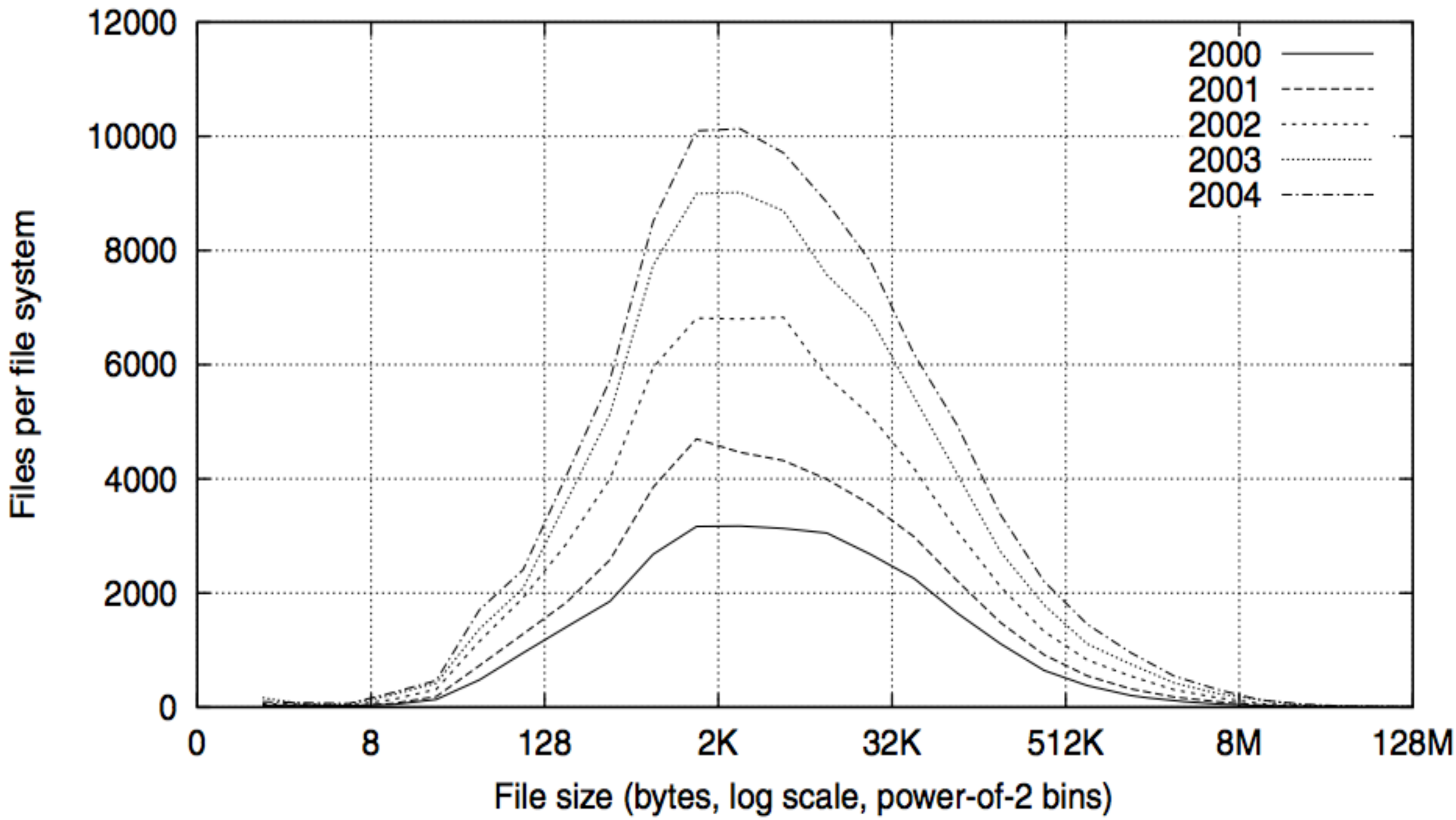


Fig. 2. Histograms of files by size.

Characteristics of Files

- Most of the space is occupied by the rare big ones

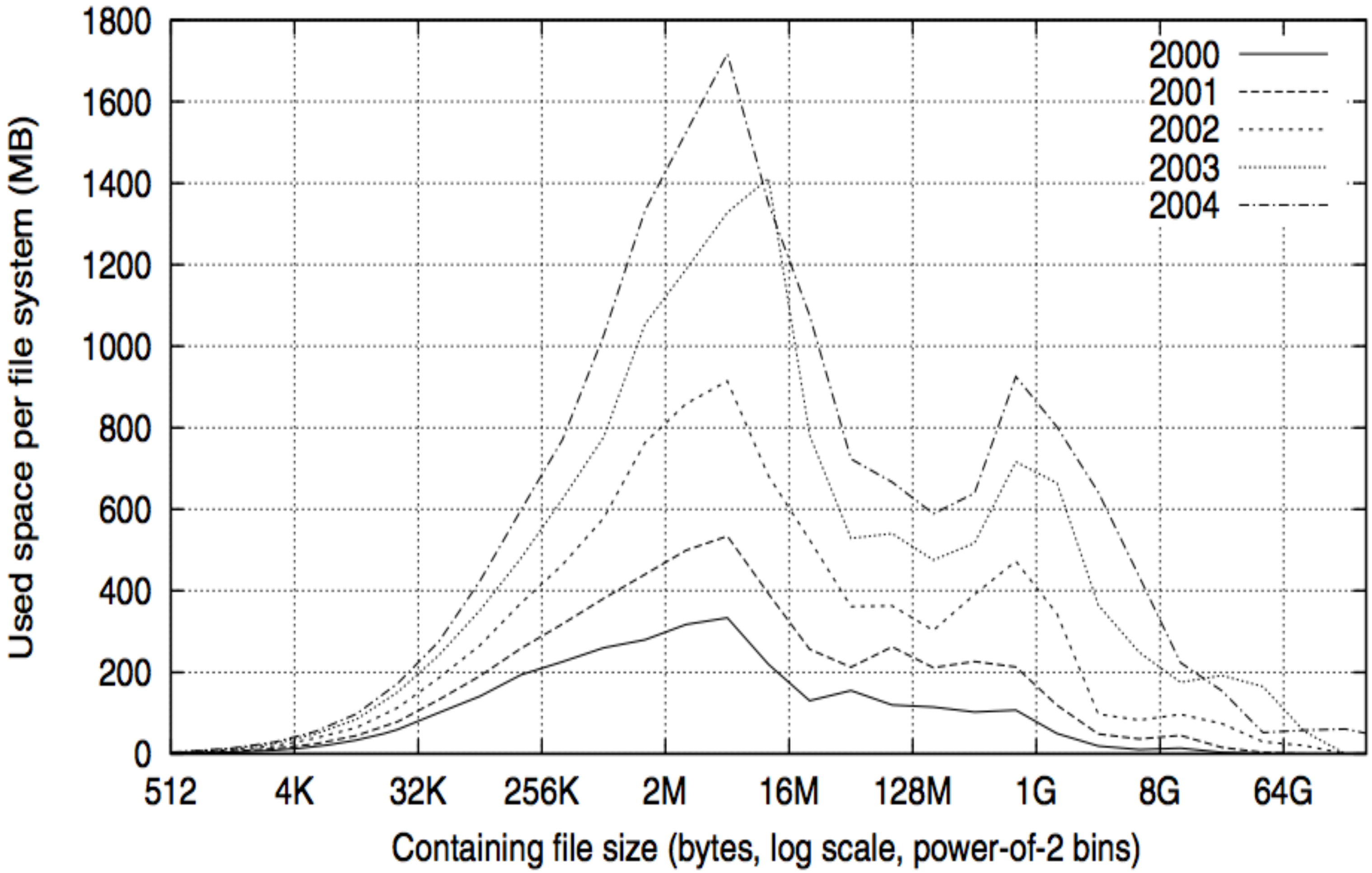


Fig. 4. Histograms of bytes by containing file size.

Unix File System (1/2)

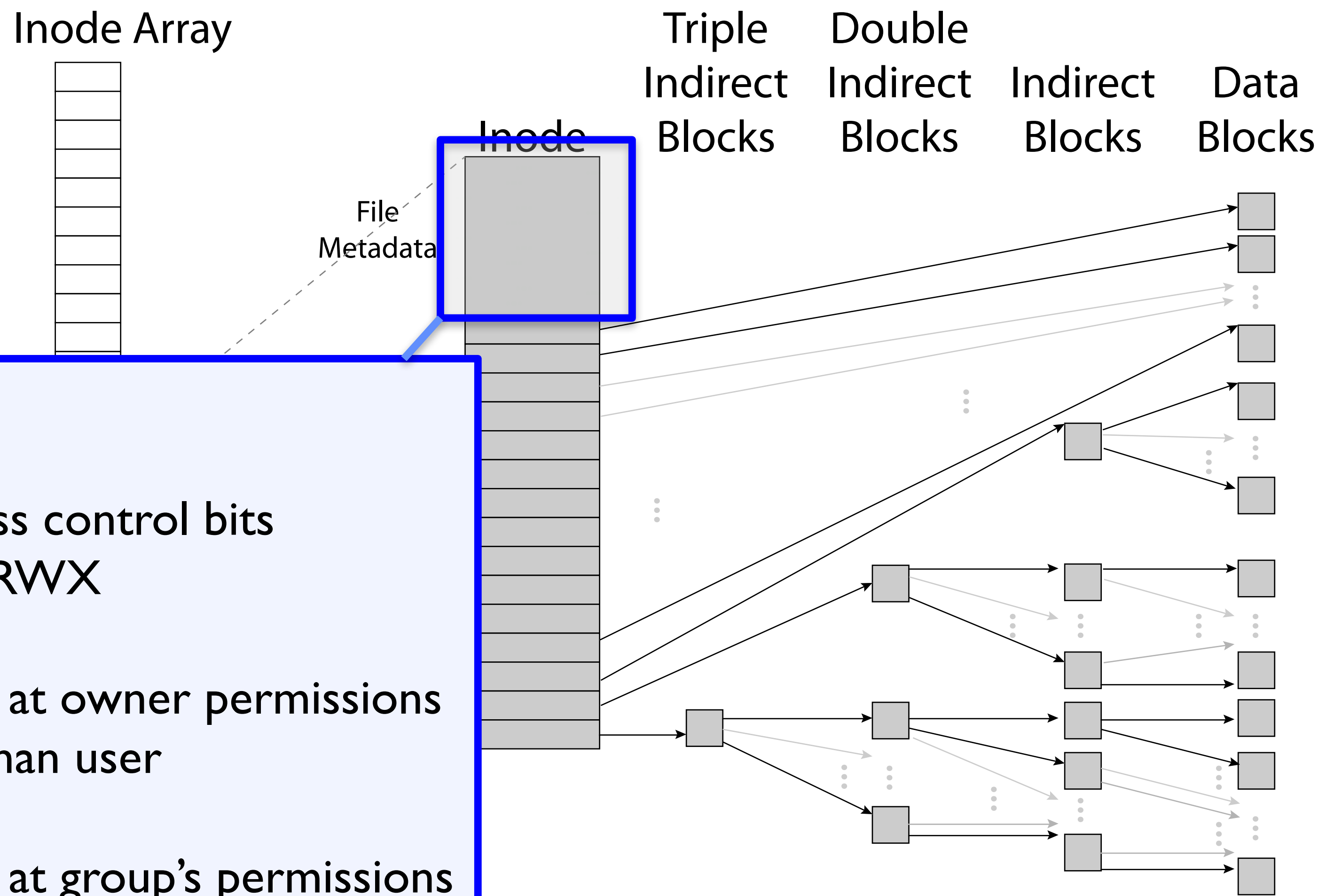
- Original inode format appeared in BSD 4.1
  - Berkeley Standard Distribution Unix
  - Part of your heritage!
  - Similar structure for Linux Ext2/3
- File Number is index into inode arrays
- Multi-level index structure
  - Great for little and large files
  - Asymmetric tree with fixed sized blocks

Unix File System (2/2)

- Metadata associated with the file
  - Rather than in the directory that points to it
- UNIX Fast File System (FFS) BSD 4.2 Locality Heuristics:
  - Block group placement
  - Reserve space
- Scalable directory structure

File Attributes

- inode metadata



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

Data Storage

- Small files: 12 pointers direct to data blocks

Direct pointers

4kB blocks ⇒ sufficient for files up to 48KB

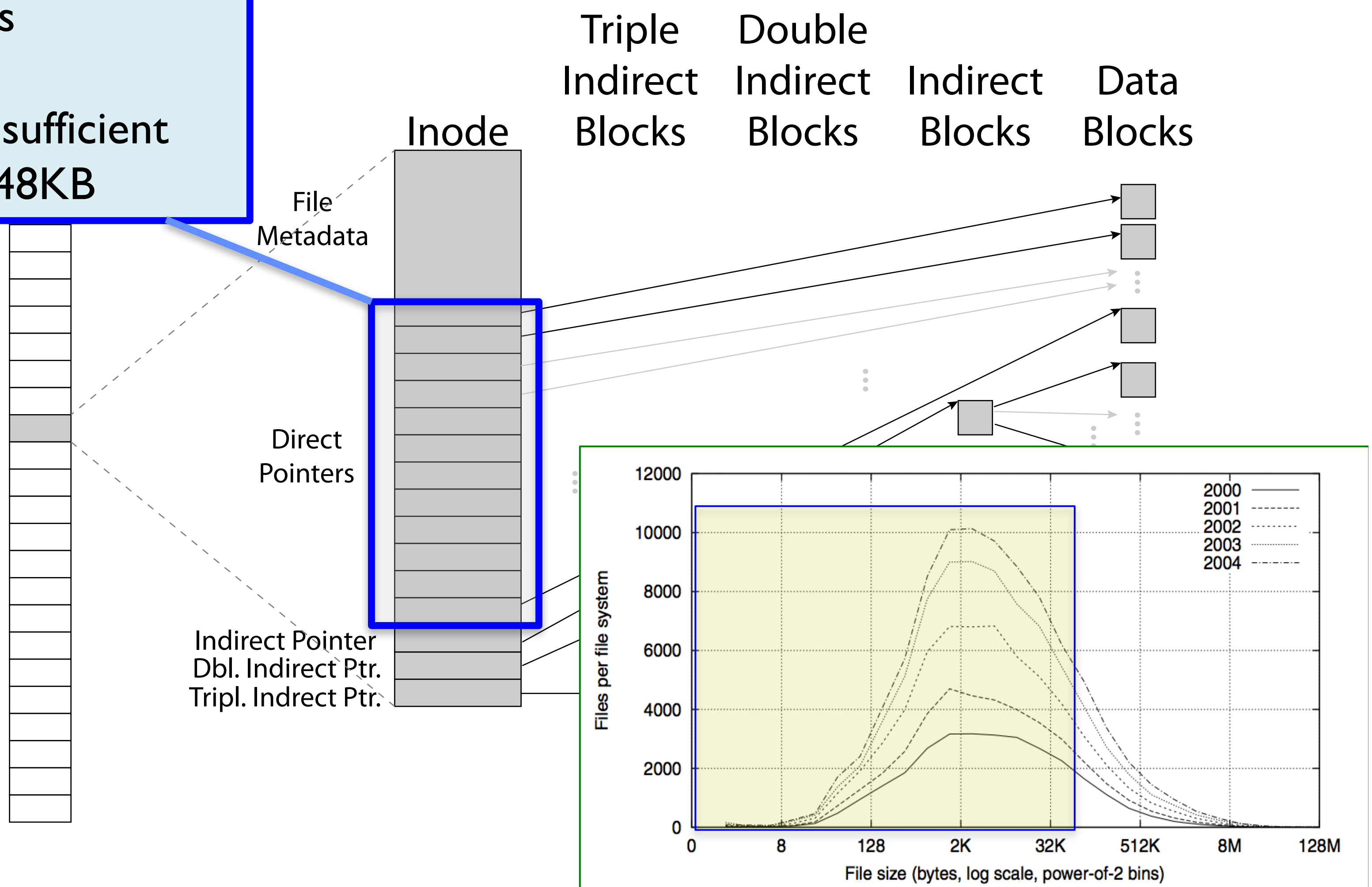
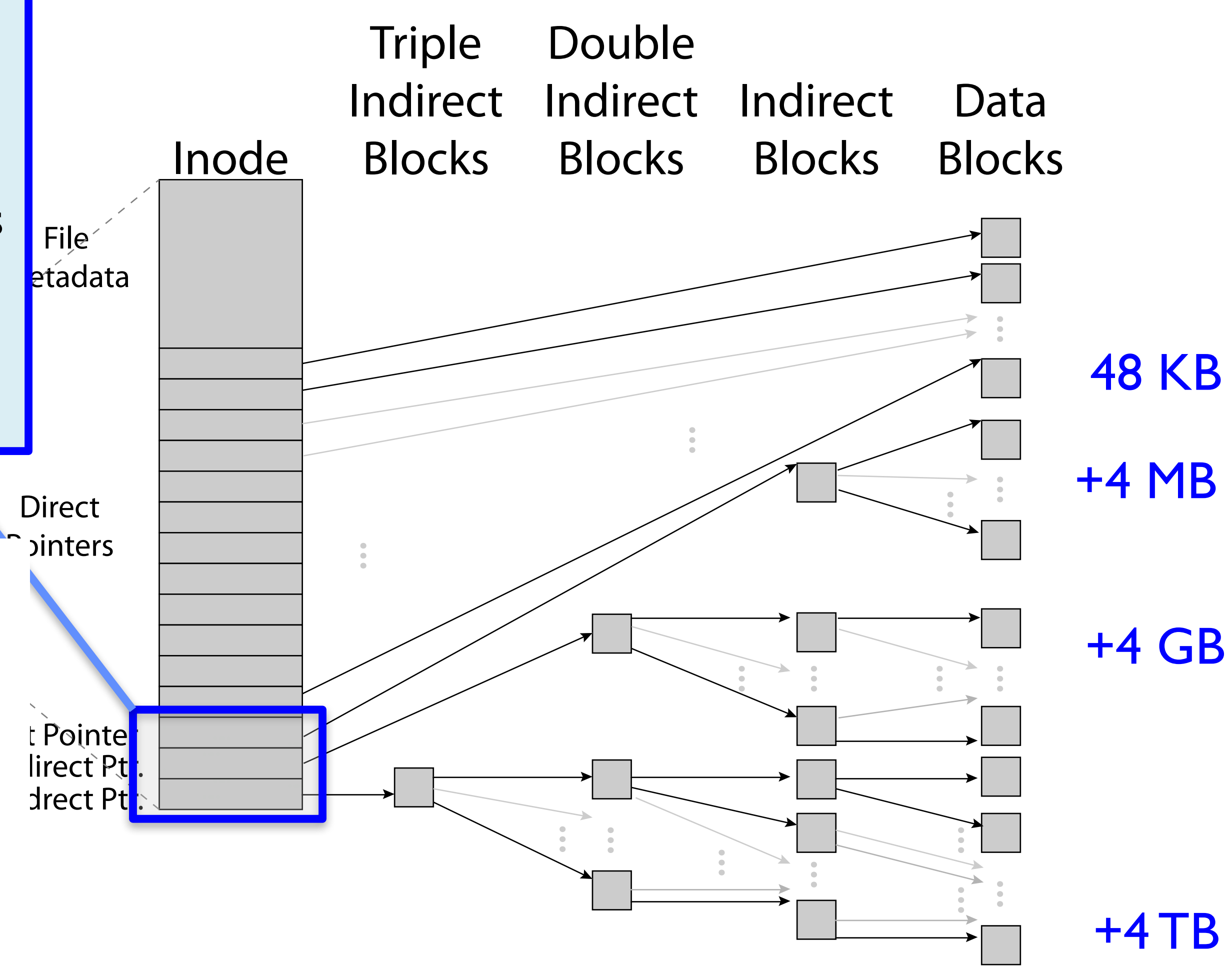


Fig. 2. Histograms of files by size.

Data Storage

- 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



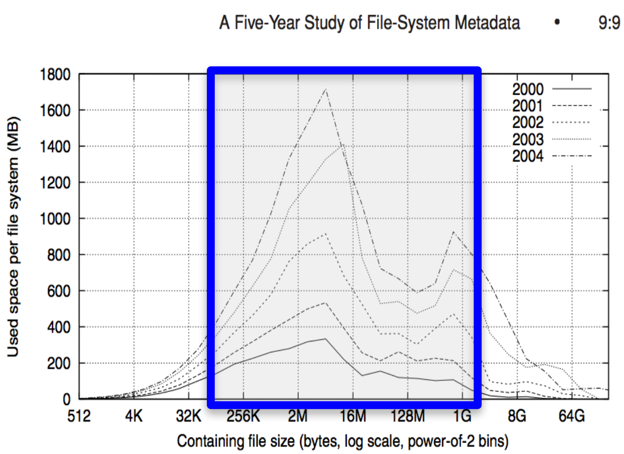


Fig. 4. Histograms of bytes by containing file size.

UNIX BSD 4.2 (1984) (1/2)

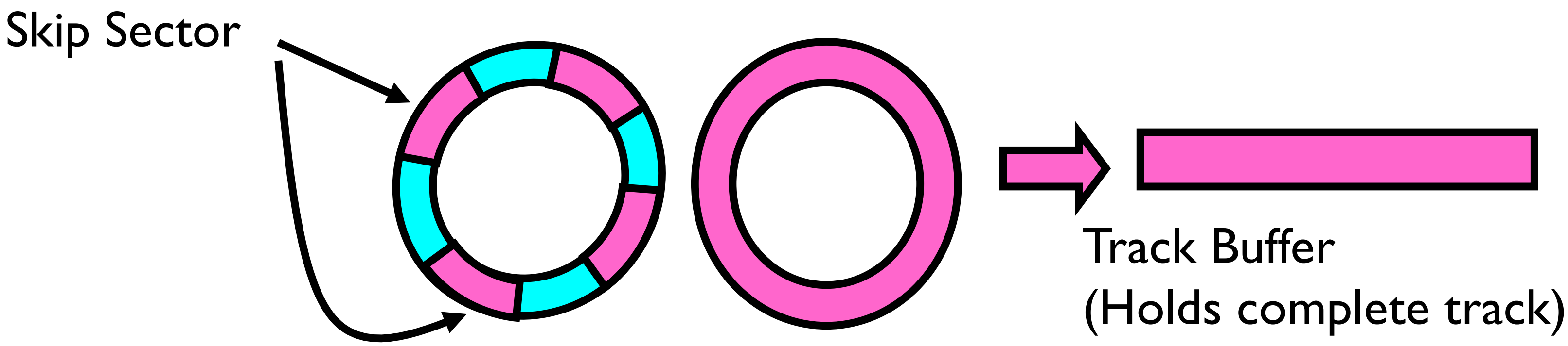
- Same as BSD 4.1 (same file header and triply indirect blocks), except incorporated ideas from Cray Operating System:
  – Uses bitmap allocation in place of freelist
  – Attempt to allocate files contiguously
  – 10% reserved disk space
  – Skip-sector positioning (mentioned later)

UNIX BSD 4.2 (1984) (2/2)

- 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 BSD 4.2, just find some range of free blocks
    - » Put each new file at the front of different range
    - » To expand a file, you first try successive blocks in bitmap, then choose new range of blocks
  - Also in BSD 4.2: store files from same directory near each other
- Fast File System (FFS)
  - Allocation and placement policies for BSD 4.2

Attack of the Rotational Delay

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



  - Solution1: Skip sector positioning ("interleaving")
    » Place the blocks from one file on every other block of a track: give time for processing to overlap rotation
    » Can be done by OS or in modern drives by the disk controller

Attack of the Rotational Delay

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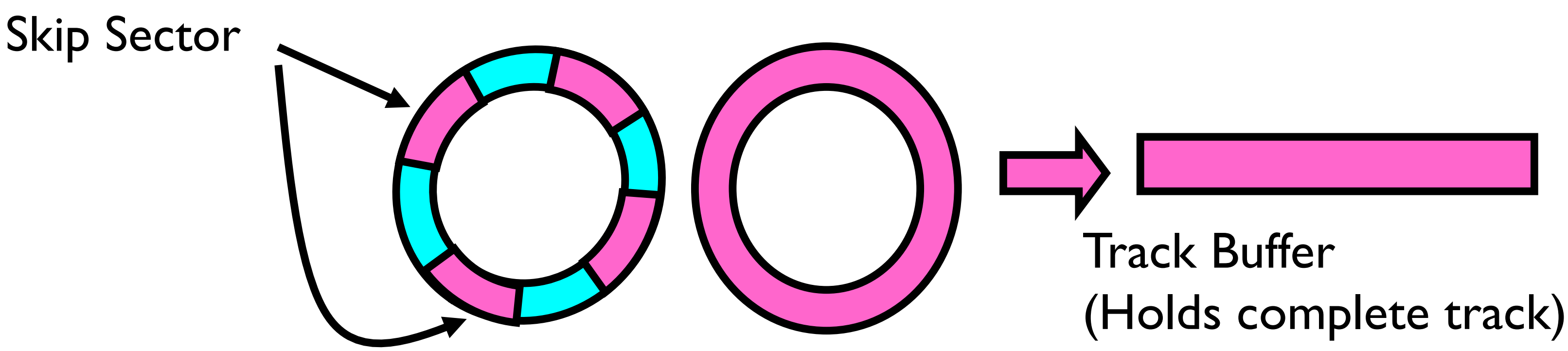


  - Solution 2: Read ahead: read next block right after first, even if application hasn't asked for it yet
    - » This can be done either by OS (read ahead)
    - » By disk itself (track buffers) - many disk controllers have internal RAM that allows them to read a complete track
- Note: Modern disks + controllers do many things "under the covers"
  - Track buffers, elevator algorithms, bad block filtering

Where are inodes Stored?

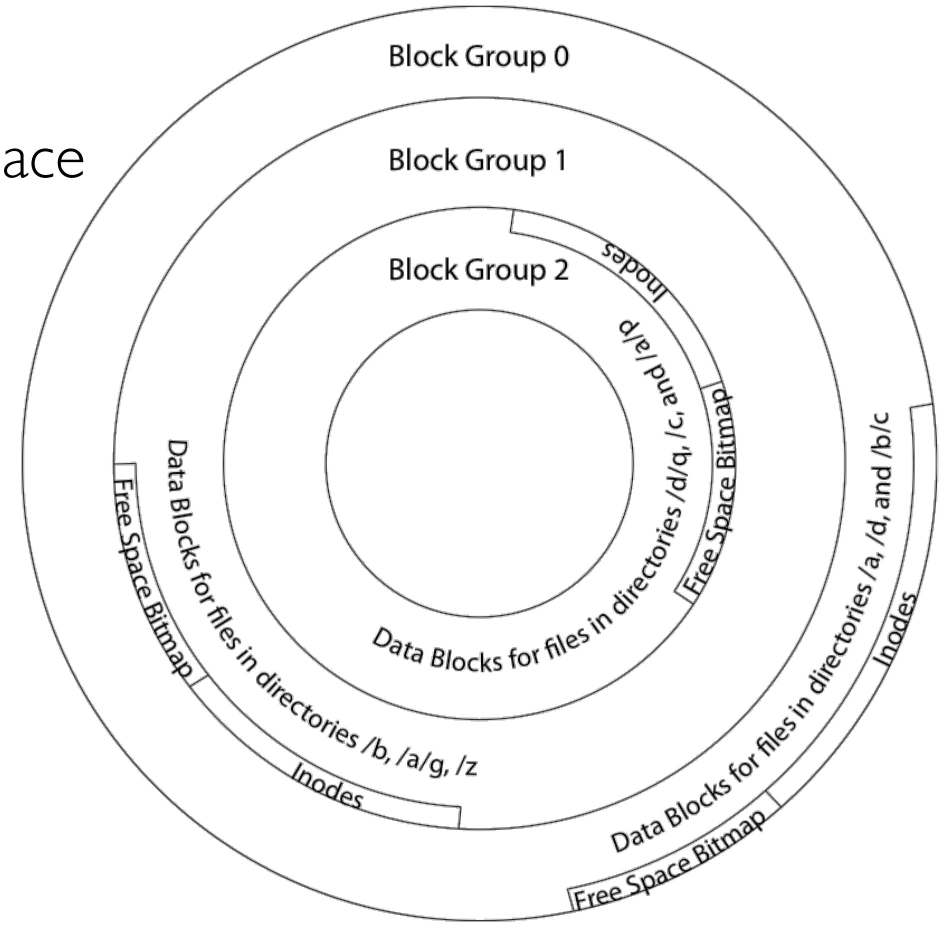
- In early UNIX and DOS/Windows' FAT file system, headers stored in special array in outermost cylinders
- Header not stored anywhere near the data blocks
  - To read a small file, seek to get header, seek back to data
- Fixed size, set when disk is formatted
  - At formatting time, a fixed number of inodes are created
  - Each is 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 bit of file header array on many cylinders
  - 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)
- Part of the Fast File System (FFS)
  - General optimization to avoid seeks

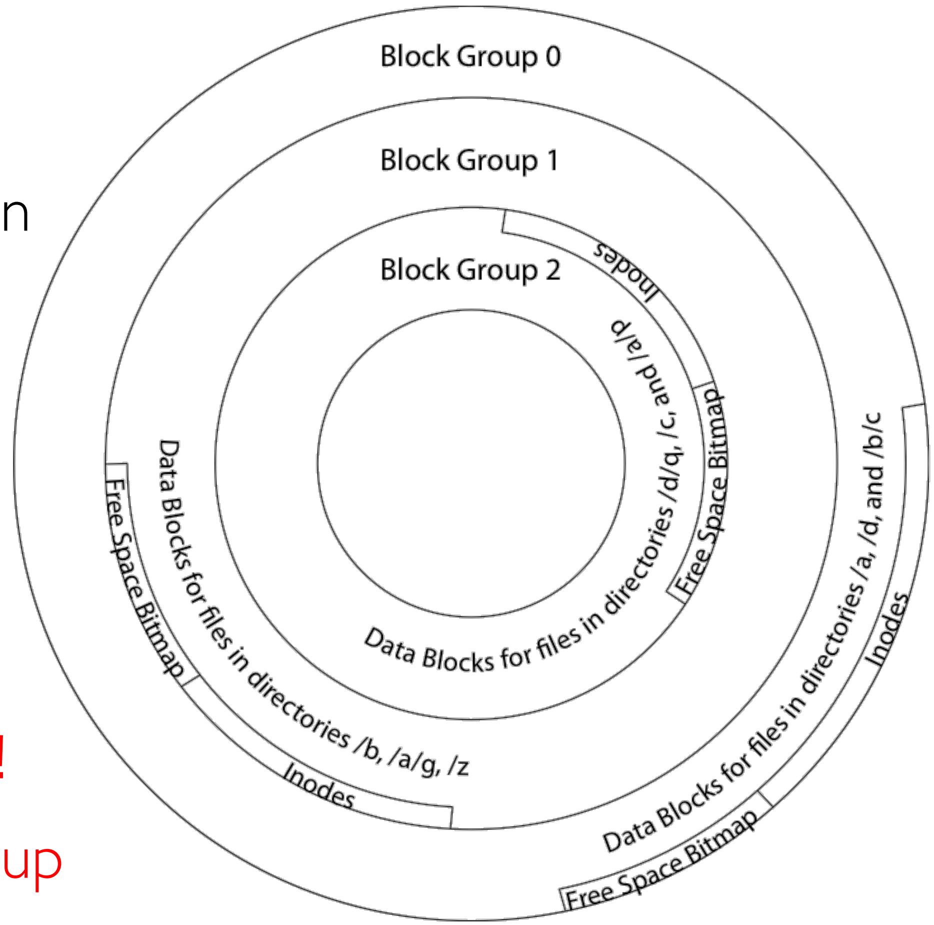
4.2 BSD Locality: Block Groups

- File system volume is divided into a 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

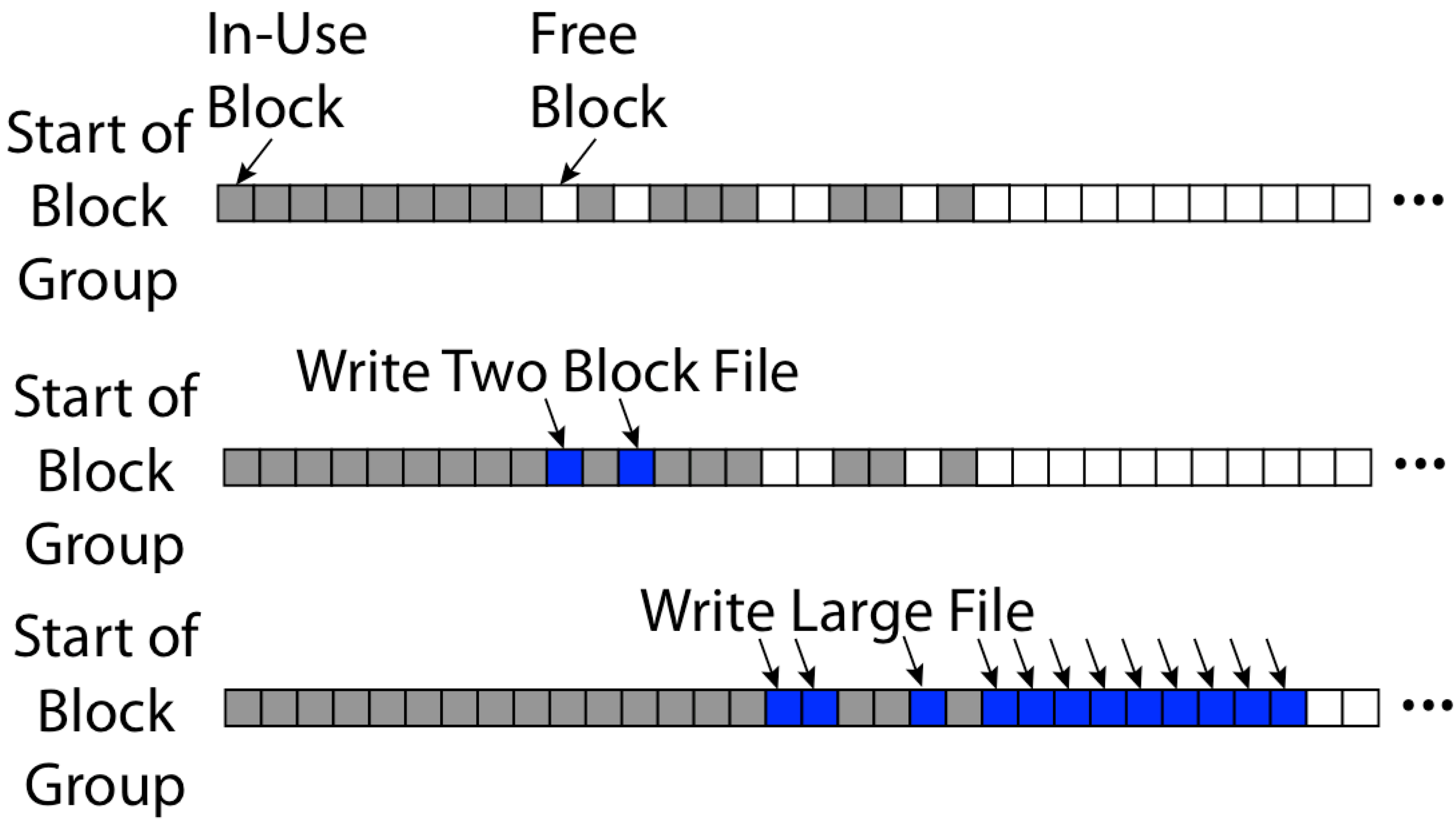


4.2 BSD Locality: Block Groups

- 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



UNIX 4.2 BSD FFS First Fit Block Allocation



UNIX 4.2 BSD FFS

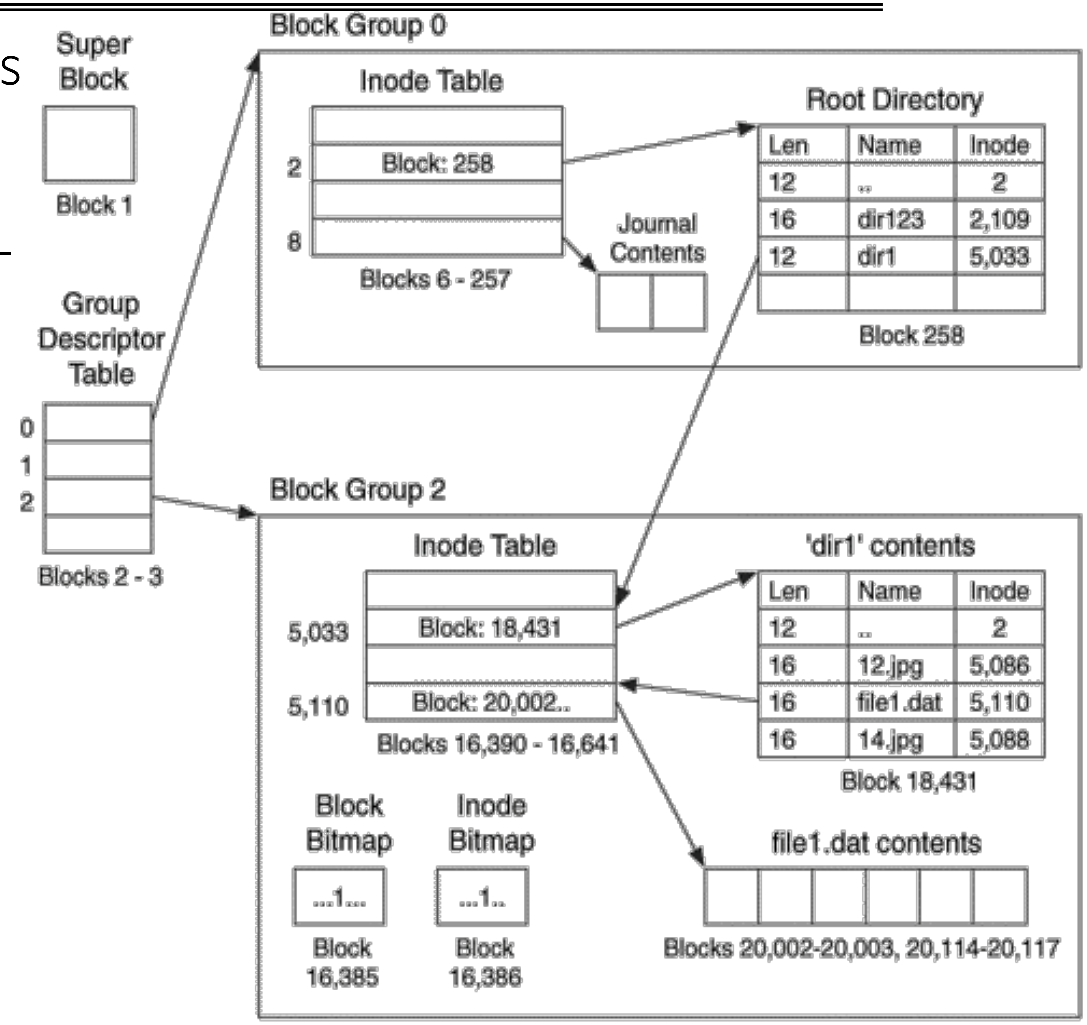
- Pros
  - Efficient storage for both small and large files
  - Locality for both small and large files
  - Locality for metadata and data
  - No defragmentation necessary!

- 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

BREAK

Linux Example: Ext2/3 Disk Layout

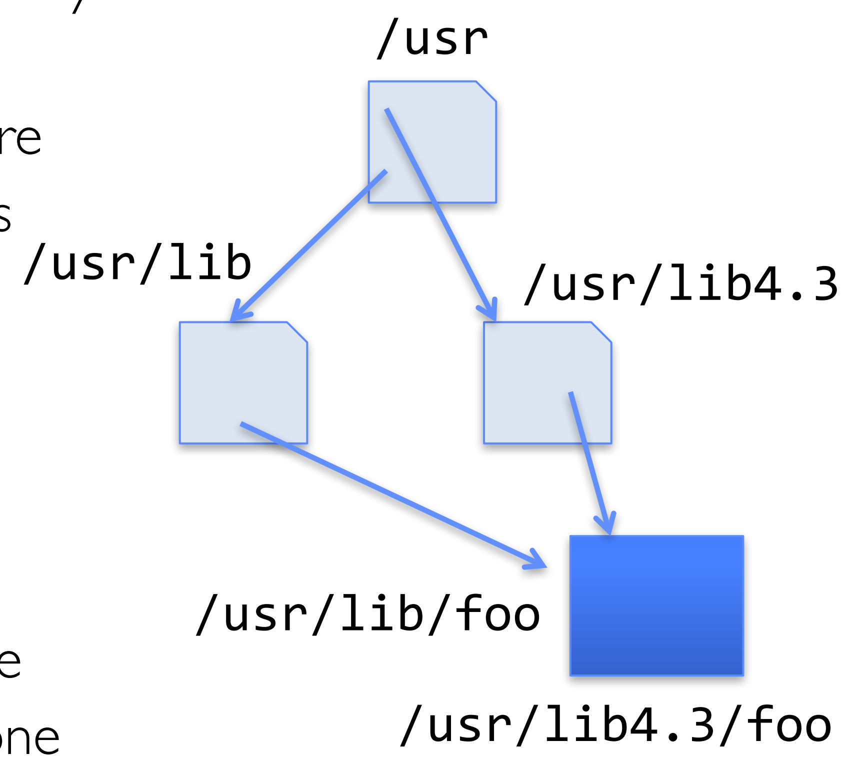
- Disk divided into block groups
  - Provides locality
  - Each group has two block-sized bitmaps (free blocks/inodes)
  - Block sizes settable at format time: 1K, 2K, 4K, 8K…
- Actual inode structure similar to 4.2 BSD
  - with 12 direct pointers
- Ext3: Ext2 with Journaling
  - Several degrees of protection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



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

A bit more on directories

- Stored in files, can be read, but typically don't
  - System calls to access directories
  - `open` / `creat` traverse the structure
  - `mkdir` /`rmdir` add/remove entries
  - `link` / unlink (`rm`)
    - » Link existing file to a directory
      - Not in FAT !
    - » Forms a DAG



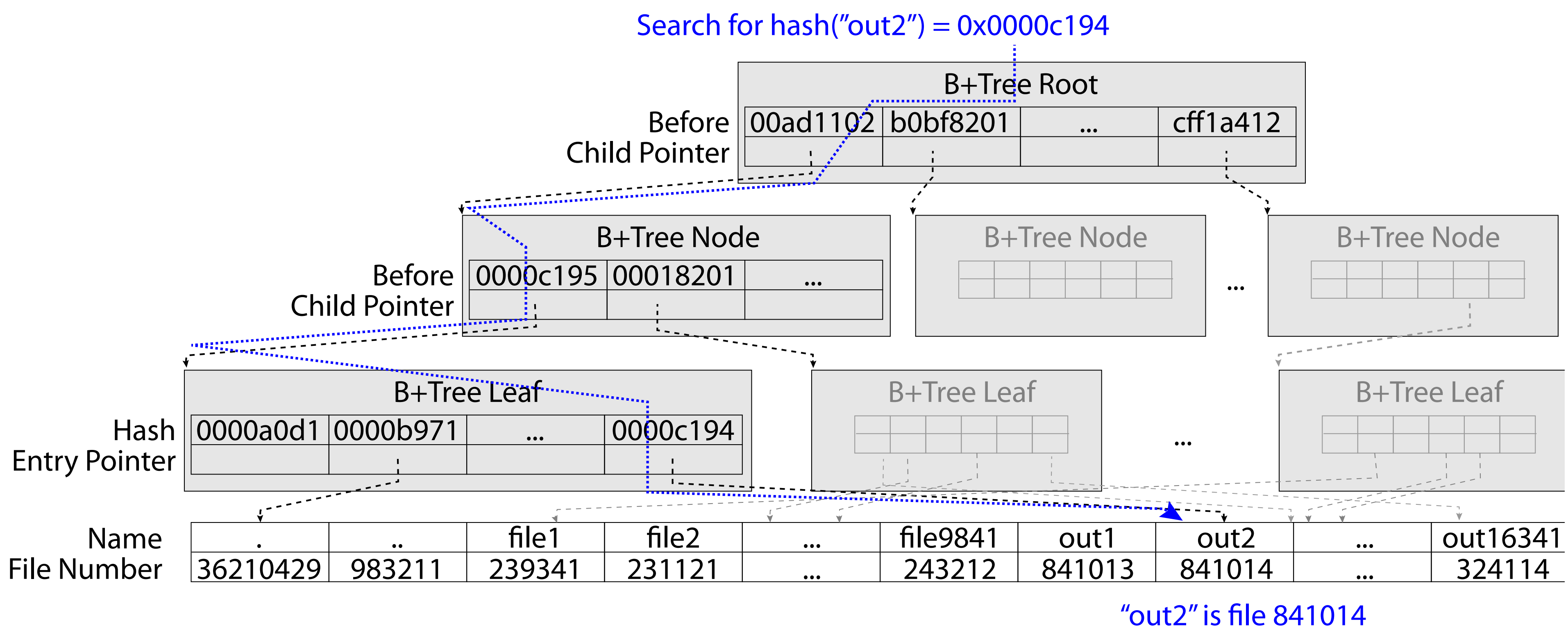
- When can file be deleted?
  - Maintain ref-count of links to the file
  - Delete after the last reference is gone
- libc support
  - `DIR * opendir (const char *dirname)`
  - `struct dirent * readdir (DIR *dirstream)`
  - `int readdir_r (DIR *dirstream, struct dirent *entry, struct dirent **result)`

Links

- Hard link
  - Sets another directory entry to contain the file number for the file
  - Creates another name (path) for the file
  - Each is "first class"
- Soft link or Symbolic Link or Shortcut
  - Directory entry contains the path and name of the file
  - Map one name to another name

Large Directories: B-Trees (dirhash)

in FreeBSD, NetBSD, OpenBSD

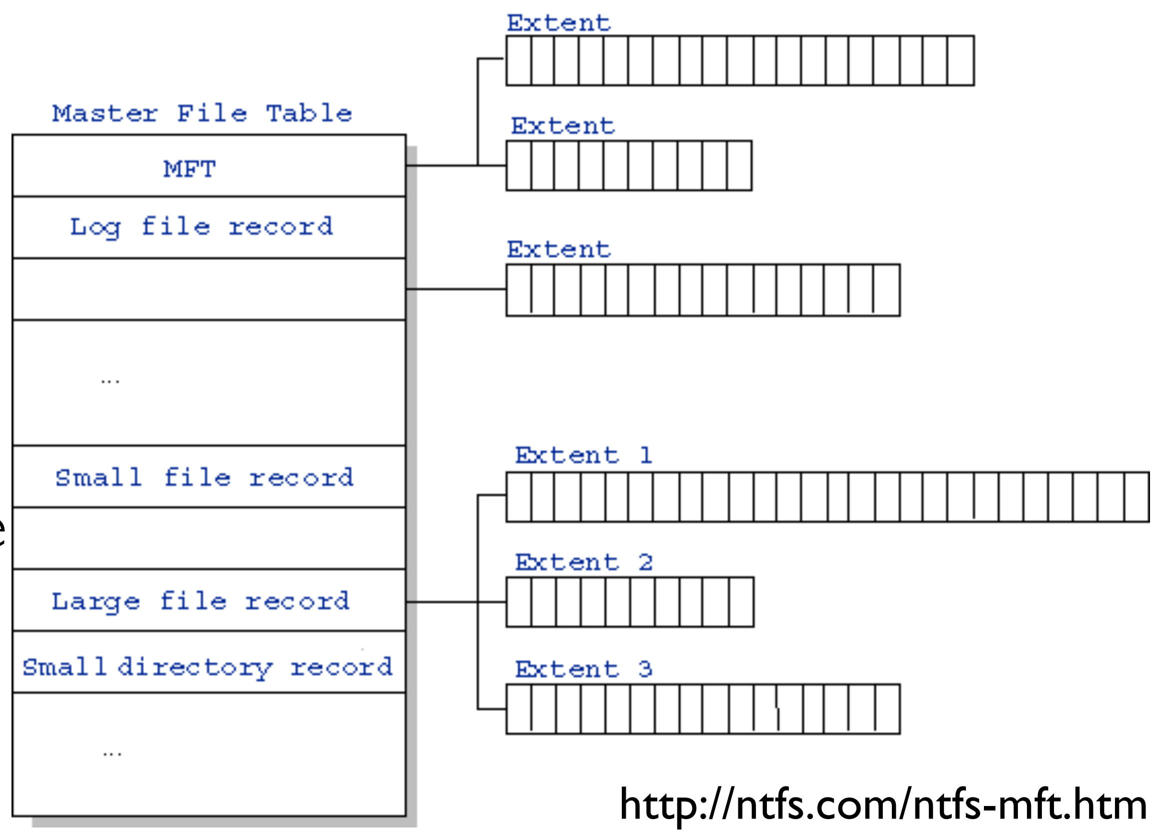


NTFS

- New Technology File System (NTFS)
  - Default on Microsoft Windows systems
- Variable length extents
  - Rather than fixed blocks
- Everything (almost) is a sequence of <attribute:value> pairs
  - Meta-data and data
- Mix direct and indirect freely
- Directories organized in B-tree structure by default

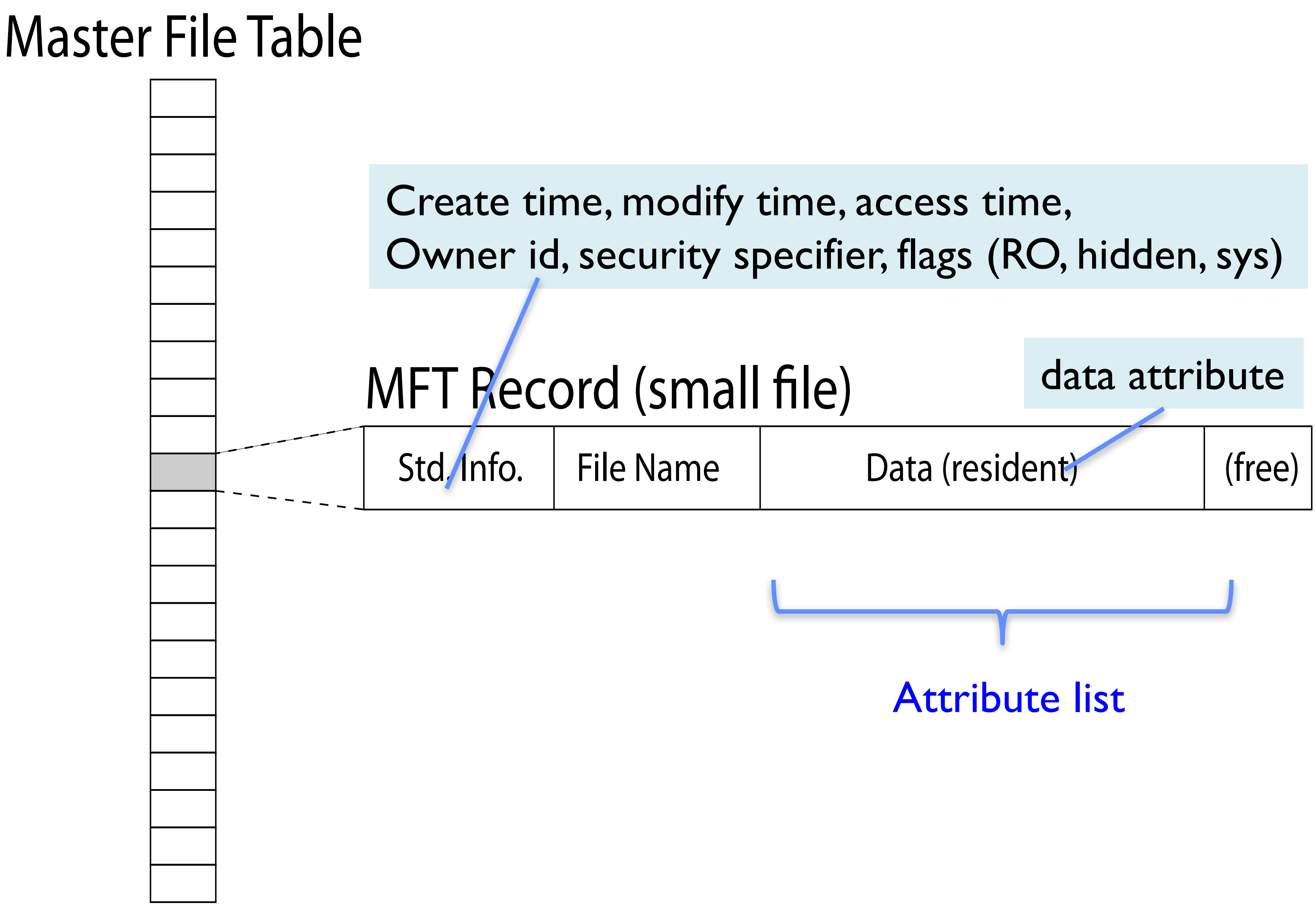
NTFS

- 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

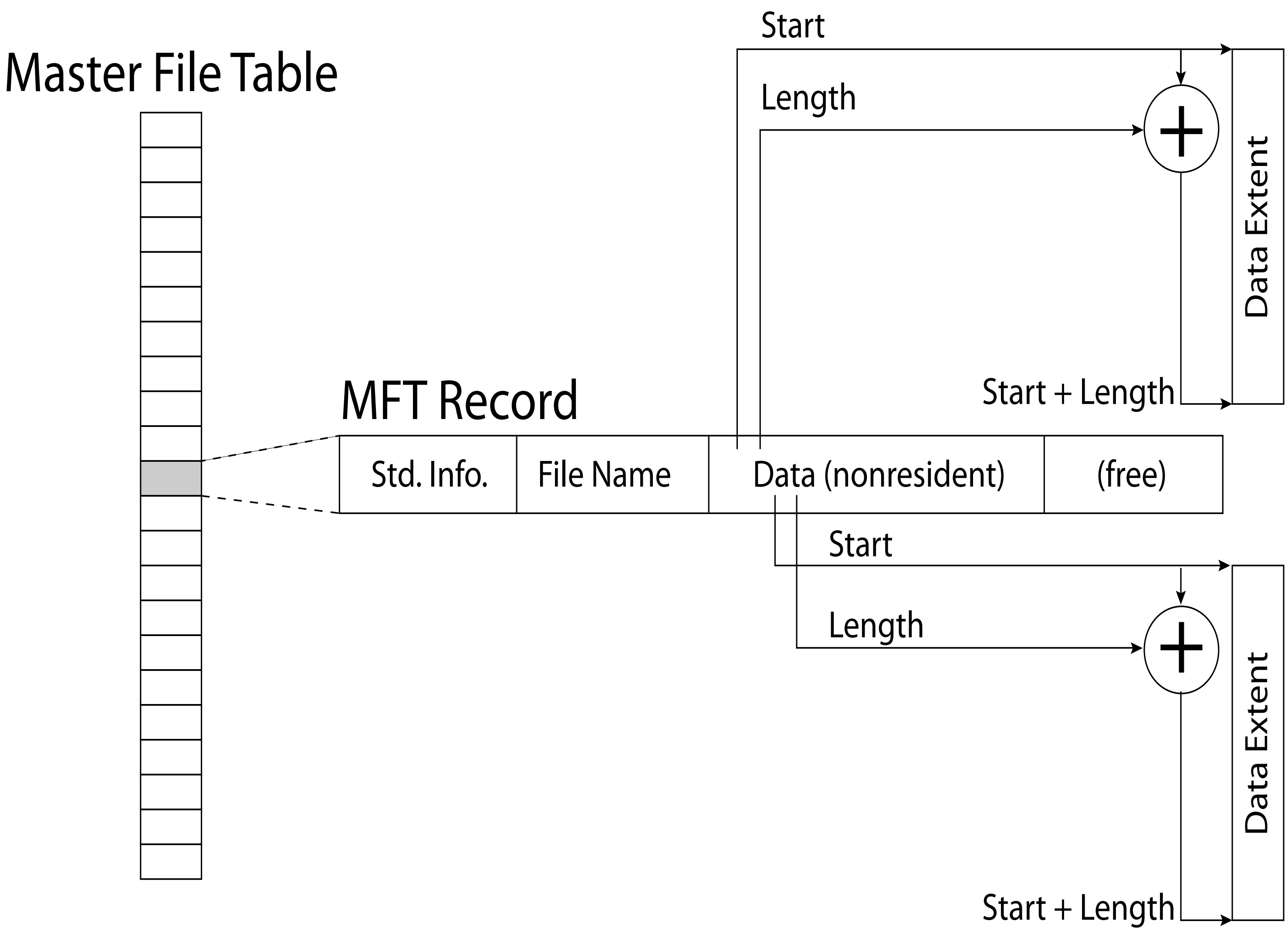


http://ntfs.com/ntfs-mft.htm

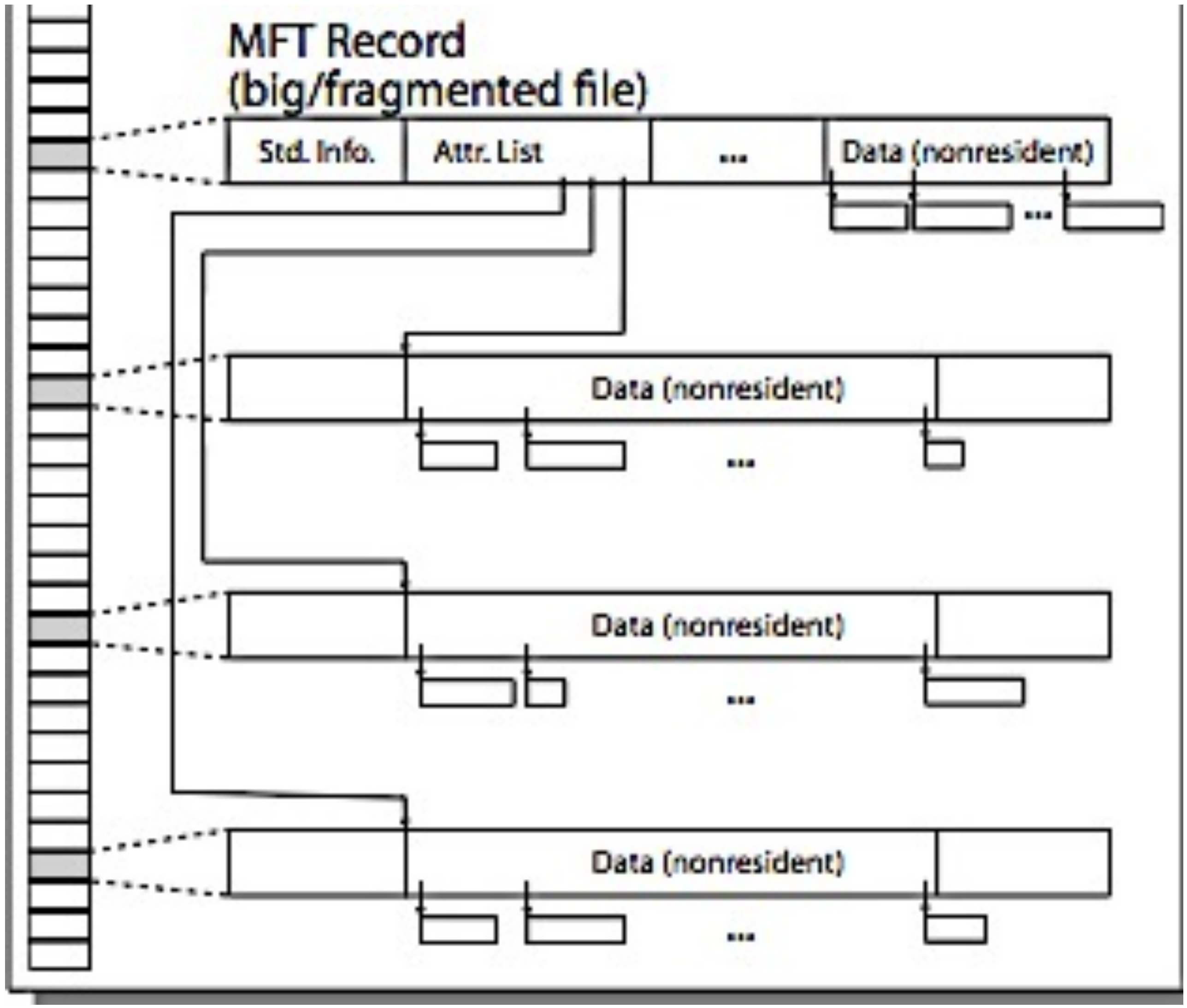
NTFS Small File

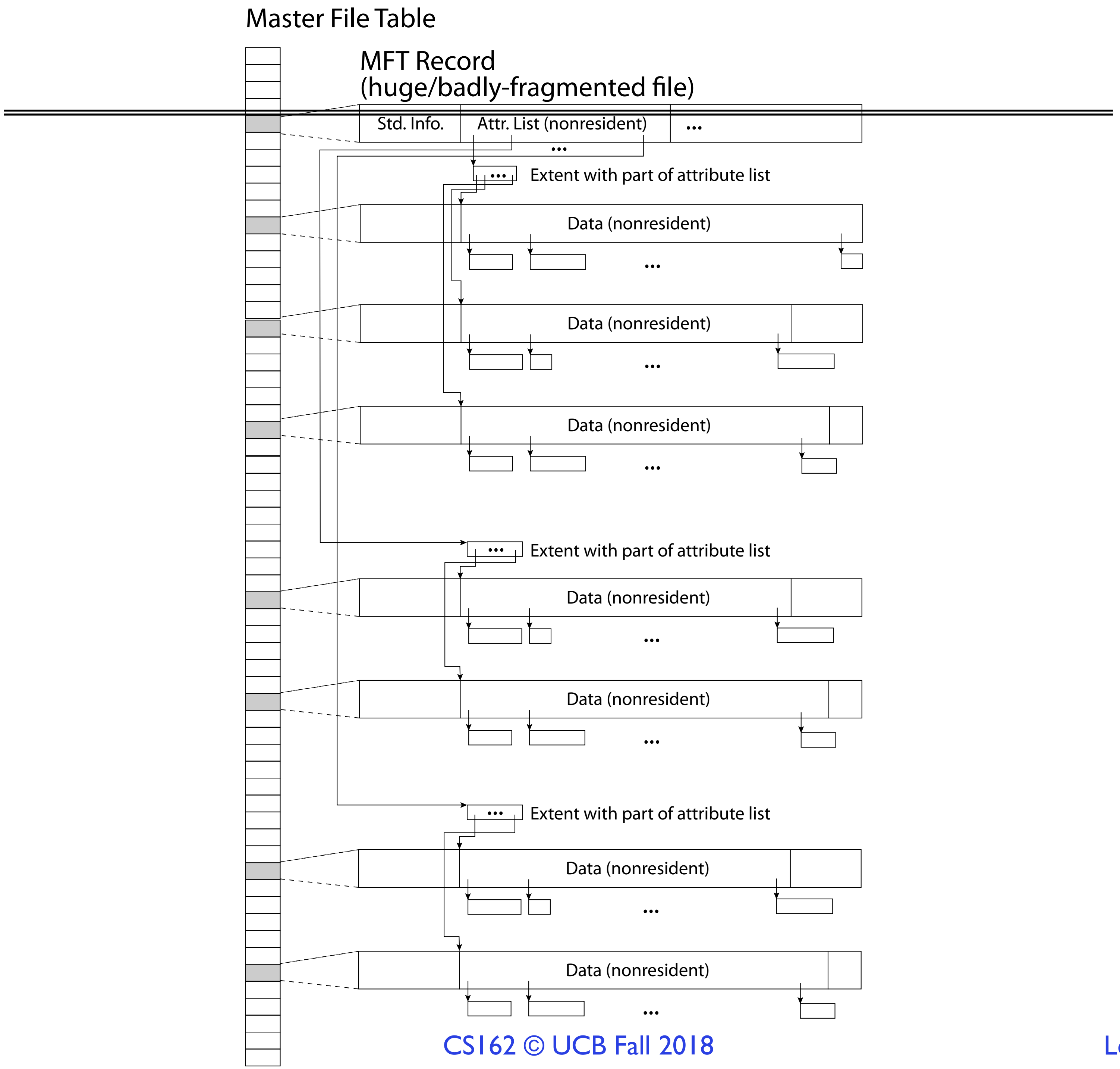


NTFS Medium File



NTFS Multiple Indirect Blocks

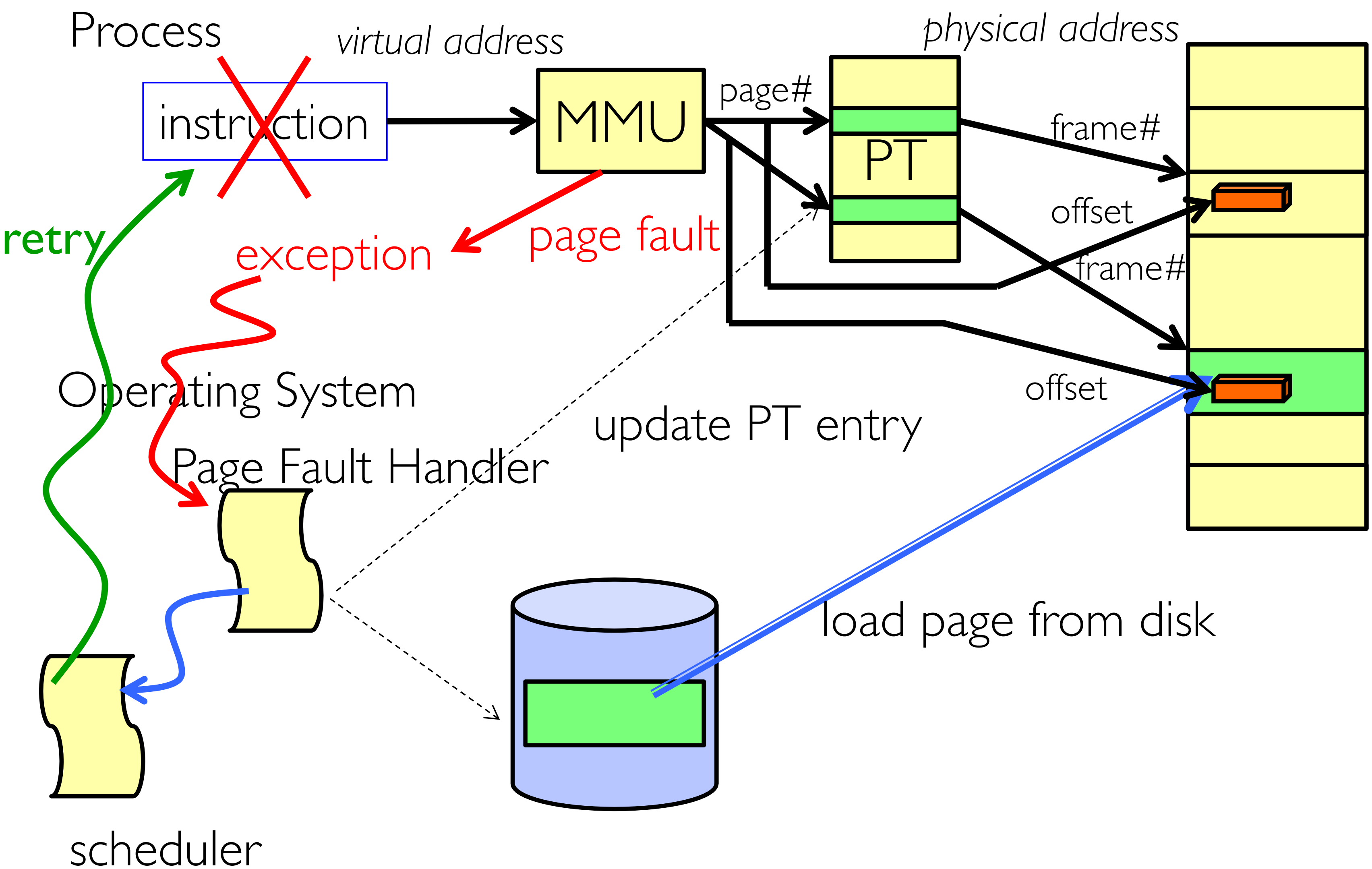



Master File Table
MFT Record
(huge/badly-fragmented file)
Std. Info.
Attr. List (nonresident)
...
Extent with part of attribute list
Data (nonresident)
Data (nonresident)
Data (nonresident)
Extent with part of attribute list
Data (nonresident)
Data (nonresident)
Extent with part of attribute list
Data (nonresident)
Data (nonresident)

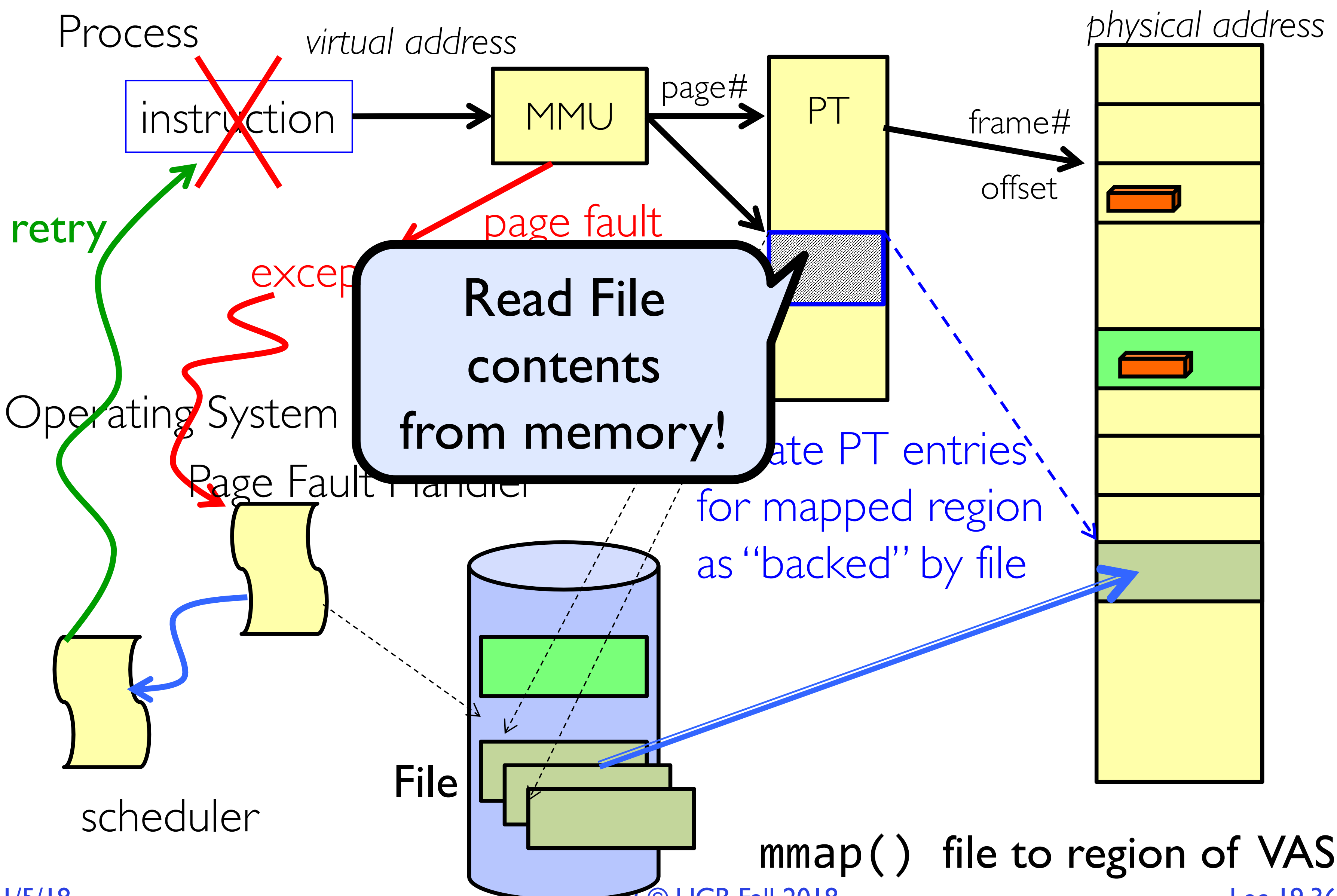
Memory Mapped Files

- 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
- 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
```

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
- 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)

- 4.2 BSD Multilevel index files
  - Inode contains ptrs to actual blocks, indirect blocks, double indirect blocks, etc.
  - Optimizations for sequential access: start new files in open ranges of free blocks, rotational optimization
- File layout driven by freespace management
  - 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