Files and File Systems

- 11A File Semantics
- 11B File Representation
- 11D Free-Space Representation

What is a File

- a file is a named collection of information
- primary roles of file system:
  - to store and retrieve data
  - to manage the media/space where data is stored
- typical operations:
  - where is the first block of this file
  - where is the next block of this file
  - where is block 35 of this file
  - allocate a new block to the end of this file
  - free all blocks associated with this file

Data and Metadata

- File systems deal with two kinds of information
- *Data* – the contents of the file
  - e.g. instructions of the program, words in the letter
- *Metadata* – Information about the file
  - e.g. how many bytes are there, when was it created
  - sometimes called *attributes*
- both must be persisted and protected
  - stored and connected by the file system

Sequential Byte Stream Access

```
int infd = open("abc", O_RDONLY);
int outfd = open("xyz", O_WRONLY+O_CREATE, 0666);
if (infd >= 0 && outfd >= 0) {
    int count = read(infd, buf, sizeof buf);
    while( count > 0 ) {
     write(outfd, buf, count);
     count = read(infd, inbuf, BUFSIZE);
    }
    close(infd);
    close(outfd);
}
```


Random Access

```
void *readSection(int fd, struct hdr *index, int section) {
    struct hdr *head = &hdr[section];
    off_t offset = head->section_offset;
    size_t len = head->section_length;
    void *buf = malloc(len);
    if (buf != NULL) {
     lseek(fd, offset, SEEK_SET);
     if (read(fd, buf, len) <= 0) {
          free(buf);
          buf = NULL;
     }
    }
    return(buf);
}
```


Consistency Model

- When do new readers see results of a write?
  - read-after-write
    - as soon as possible, data-base semantics
    - this commonly called "POSIX consistency"
  - read-after-close (or sync/commit)
    - only after writes are committed to storage
  - open-after-close (or sync/commit)
    - each open sees a consistent snapshot
  - explicitly versioned files
    - each open sees a named, consistent snapshot

File Attributes – basic properties

- thus far we have focused on a simple model
  - a file is a "named collection of data blocks"
- in most OS files have more state than this
  - file type (regular file, directory, device, IPC port)
  - valid data length (excluding end of last block)
  - ownership and protection information
  - system attributes (e.g. hidden, archive)
  - time of creation, modification, last access
- typically stored in *file descriptor* structure

Extended File Types and Attributes

- extended protection information
  - e.g. access control lists
- resource forks
  - e.g. configuration data, message, related objects
- application defined types
  - e.g. load modules, HTML, e-mail, MPEG, ...
- application defined properties
  - e.g. compression scheme, encryption algorithm, ...

Relational Databases

- a tool managing business critical data
- table is equivalent of a file system
- data organized in rows and columns
  - row indexed by unique key
  - columns are named fields within each row
- support a rich set of operations
  - multi-object, read/modify/write transactions
  - insert/delete row/column operations
- SQL searches designed for human querents

Key-Value Stores

- smaller and faster than an SQL database
  - optimized for frequent small transfers
- *table* is equivalent of a file system
  - a *table* is a collection of *key/value* pairs
- *keys* have long names in a flat name space
  - *key* names are unique within a *table*
- value is a (typically 64-64MB) string
  - get/put (entire value)
  - delete
  - may support *ranged queries*

Object Stores

- simplified file systems, cloud storage
  - optimized for large but infrequent transfers
  - becoming a dominant storage model
- *bucket* is equivalent of a file system
  - a *bucket* contains named, versioned *objects*
- *objects* have long names in a flat name space
  - *object* names are unique within a *bucket*
- an *object* is a blob of *immutable* bytes
  - get … all or part of the *object*
  - put … new version, there is no *append/update*
  - delete

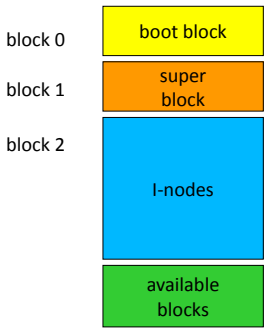
File System Goals

- ensure the privacy and integrity of all files
- efficiently implement name-to-file binding
  - find file associated with this name
  - list the file names in this part of the name space
- efficiently manage data associated w/each file
  - return data at offset X in file Y
  - write data Z at offset X in file Y
- manage attributes associated w/each file
  - what is the length of file Y
  - change owner/protection of file Y to be X

File System Structure

- direct access volumes made of fixed-sized blocks
  - many sizes are used: 512, 1024, 2048, 4096, 8192 ...
- most of them will store user data
- some will store organizing "meta-data"
  - description of the file system (e.g. layout and state)
  - file control blocks to describe individual files
  - lists of free blocks (not yet allocated to any file)
- all operating systems have such data structures
  - different OS and FS often have very different goals
  - these result in very different implementations

Unix System 5 – Volume Structure



block size and number of I-nodes are specified in super block

I-node #1 (traditionally) describes the root directory

data blocks begin immediately after the end of the I-nodes.

File Descriptor Structures

- all file systems have file descriptor structures
- contain all info about file
  - type (e.g. file, directory, pipe)
  - ownership and protection
  - size (in bytes)
  - other attributes
  - location of data blocks

UNIX I-node

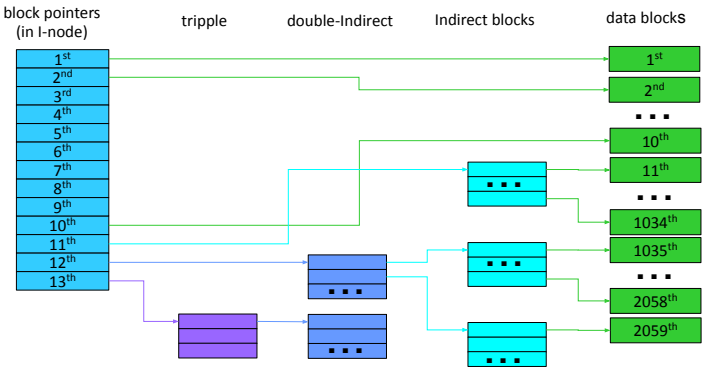
type	protection
owner	group
# links	
file size	
last access time	
last written time	
last I-node update time	
data block pointers …	

- descriptor location/# is file's *true name*

Ways to Manage Allocated Space

- a single large, contiguous *extent*
  - one pointer per file, very efficient I/O
  - hard to extend, external fragmentation, coalescing
- a linked lists of blocks
  - one pointer per file, one per extent
  - potentially long searches
- N block pointers per file
  - limits maximum file size to N blocks
  - but maybe some blocks contain pointers

Unix I-nodes and block pointers



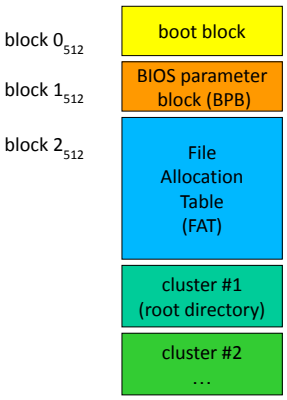
(Unix I-node block mapping)

- I-node contains 13 block pointers
  - first 10 point to first 10 blocks of file
  - 11th points to an indirect block (e.g. 4k bytes = 1k blocks)
  - 12th points to a double indirect block (w/1k indirect blocks)
  - 13th points to a triple indirect block (w/1k double indirs)
- assuming 4k bytes per block and 4-bytes per pointer
  - 10 direct blocks = 10 * 4K bytes = 40K bytes
  - indirect block = 1K * 4K = 4M bytes
  - double indirect = 1K * 4M = 4G bytes
  - triple indirect = 1K * 4G = 4T bytes (finite, but large)

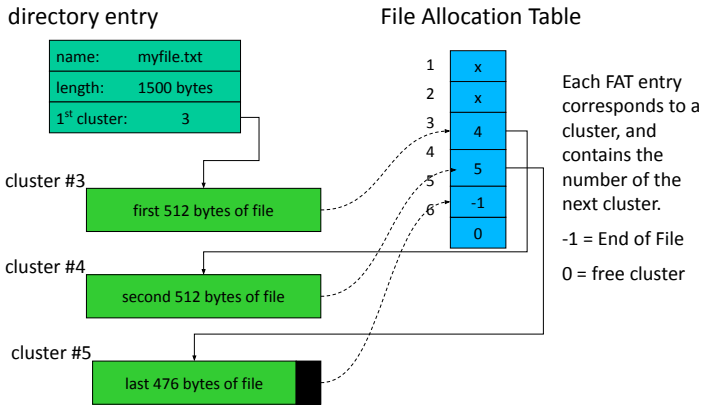
I-nodes – performance

- I-node is in memory whenever file is open
- first ten blocks can be found with no I/O
- after that, we must read indirect blocks
  - the real pointers are in the indirect blocks
  - sequential file processing will keep referencing it
  - block I/O will keep it in the buffer cache
- 1-3 extra I/O operations per thousand pages
  - any block can be found with 3 or fewer reads
- index blocks can support "sparse" files
- block # width determines max file system size

DOS FAT – Volume Structure



Clusters in a DOS FAT File



(DOS FAT File Systems – Overview)

- DOS file systems divide space into "clusters"
  - cluster size (times 512) fixed for each file system
  - clusters are numbered 1 though N
- File descriptor points to first cluster of file
- File Allocation Table (FAT), one entry/cluster
  - has number of next cluster in file
  - 0 -> cluster is not allocated
  - -1 -> end of file

FAT – Performance/Capabilities

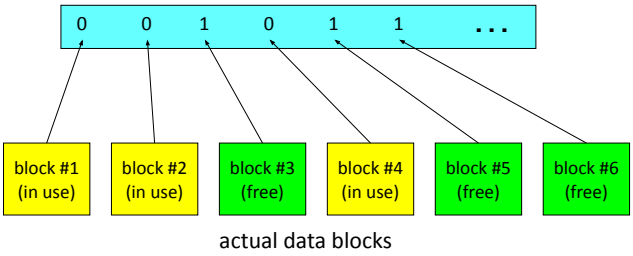
- to find a particular block of a file
  - get number of first cluster from directory entry
  - follow chain of pointers through FAT
- entire File Allocation Table is kept in memory
  - no disk I/O is required to find a cluster
  - for very large files the search can still be long
- no support for "sparse" files
  - if a file has a block n, it must have all blocks < n
- width of FAT determines max file system size

Free Space Maintenance

- file system manager manages the free space
- get/release chunk should be fast operations
  - they are extremely frequent
  - we'd like to avoid doing I/O as much as possible
- unlike memory, it matters what chunk we choose
  - best to allocate new space in same cylinder as file
  - user may ask for contiguous storage
- file system free-list organization must address
  - speed of allocation and de-allocation
  - ability to allocate contiguous or near-by space
  - ability to coalesce and de-fragment

Bit Map Free Lists

free block bit map: one bit per block

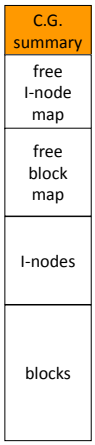


BSD file systems use bit-maps to keep track of both free blocks and free I-nodes in each cylinder group

(free space bit-maps)

- fixed sized blocks simplify free-lists
  - equal sized blocks do not require size information
  - all blocks are fungible (modulo performance)
- bit maps are a very efficient representation
  - minimal space to store the map
  - very code and cache efficient to search
- bit maps enable efficient allocation
  - easy to find chunks in a desired area
  - easy to coalesce adjacent chunks

FFS I-nodes and Free Lists



parameters for this cylinder group

bit-map for allocated and free I-nodes in this cylinder group

bit-map for allocated and free blocks in this cylinder group

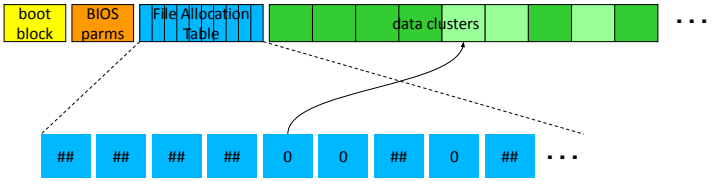
FFS create(/foo/bar)

	data bitmap	I-node bitmap	root I-node	foo I-node	bar I-node	root data	foo data	bar data[0]	bar data[1]	bar data[2]
search /			read							
search /						read				
search foo				read						
search foo							read			
new I-node		read								
new I-node		write								
update foo							write			
new I-node					read					
new I-node					write					
update foo				write						

FFS 3 x write(bar, one block)

	data bitmap	I-node bitmap	root I-node	foo I-node	bar I-node	root data	foo data	bar data[0]	bar data[1]	bar data[2]
find bar[0]					read					
new block	read									
new block	write									
write bar[1]								write		
update I-node					write					
find bar[1]					read					
new block	read									
new block	write									
write data									write	
update I-node					write					
find bar[2]					read					
new block	read									
new block	write									
write bar[2]										write
update I-node					write					

FAT Free Space



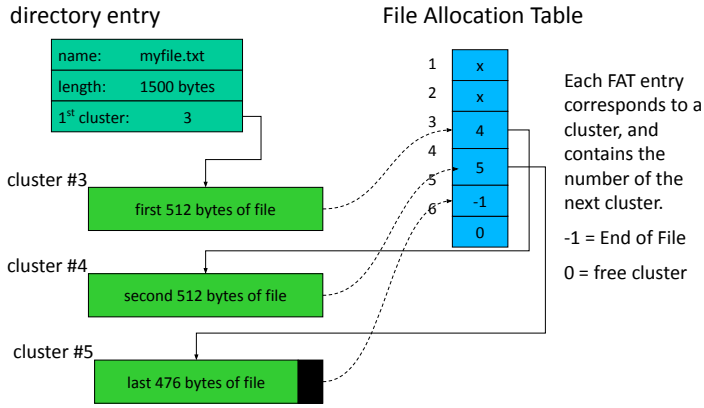
Each FAT entry corresponds to a cluster, and contains the number of the next cluster.

A value of zero indicates a cluster that is not allocated to any file, and is therefore free.

FAT Free Space

- can search for free clusters in desired cylinder
  - we can map clusters to cylinders
    - the BIOS Parameter Block describes the device geometry
  - look at first-cluster of file to choose desired cylinder
  - start search at first cluster of desired cylinder
  - examine each FAT entry until we find a free one
- if no free clusters, we must garbage collect
  - recursively search all directories for existing files
  - enumerate all of the clusters in each file
  - any clusters not found in search can be marked as free

Clusters in a DOS FAT File



(Extending a DOS/FAT file)

- note cluster number of current last cluster in file
- search FAT to find a free cluster
  - free clusters are indicated by a FAT entry of zero
  - look for a cluster in same cylinder as previous cluster
  - put -1 in FAT entry to indicate that this is the new EOF
  - this has side effect of marking new cluster as not free
- chain new cluster on to end of the file
  - put number of new cluster into FAT entry for last cluster

Reading and Assignments

Reading:

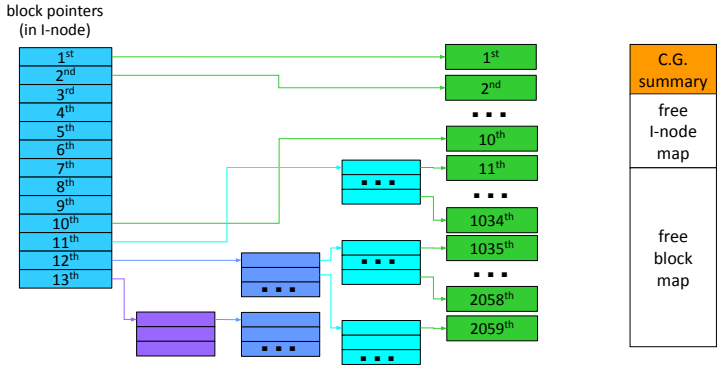
- Arpaci C39.10-15 … directories
- Arpaci C40.4 … file systems - directories

Projects:

- start looking at project 3A (file system interpretation, big)

Supplementary Slides

Unix File Extension



(Extending a BSD/UNIX file)

- note the cylinder group for the file's i-node
- note the cylinder for the previous block in the file
- find a free block in the desired cylinder
  - search the free-block bit-map for free block in right cyl
  - update bit-map to show the block has been allocated
- update the I-node to point to the new block
  - go to appropriate block pointer in I-node/indirect block
  - if new indirect block is needed, allocate/assign it first
  - update I-node/indirect to point to new block