File Systems: Semantics & Structure

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, ...)
  - file length (may be excess space at end of last block))
  - ownership and protection information
  - system attributes (e.g. hidden, archive)
  - creation time, modification time, last accessed time
- 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, fonts, related objects
- application defined types
  - e.g. load modules, HTML, e-mail, MPEG, ...
- application defined properties
  - e.g. compression scheme, encryption algorithm, ...

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
  - SQL searches return consistent snapshots
  - insert/delete row/column operations

Object Stores

- simplified file systems, cloud storage
  - optimized for large but infrequent transfers
- *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

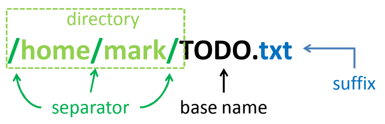
Key-Value Stores

- 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

File Names and Name Binding

- file system knows files by internal <u>descriptors</u>
- users know files by names
  - names more easily remembered than disk addresses
  - names can be structured to organize millions of files
- file system responsible for name-to-file mapping
  - associating names with new files
  - changing names associated with existing files
  - allowing users to search the name space
- there are many ways to structure a name space

What is in a Name?



- suffixes and file types
  - file-to-application binding often based on suffix
    - defined by system configuration registry
    - configured per user, or per directory
  - suffix may define the file type (e.g. Windows)
  - suffix may only be a hint (magic # defines type)

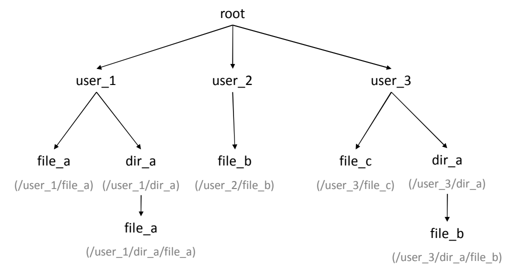
Flat Name Spaces

- there is one naming context per file system
  - all file names must be unique within that context
- all files have exactly one true name
  - these names are probably very long
- file names may have some structure
  - e.g. CAC101.CS111.SECTION1.SLIDES.LECTURE_13
  - this structure may be used to optimize searches
  - the structure is very useful to users
  - the structure has no meaning to the file system

Hierarchical Namespaces

- directory
  - a file containing references to other files
  - it can be used as a naming context
    - each process has a *current working directory*
    - names are interpreted relative to directory
- nested directories can form a tree
  - file name is a path through that tree
  - directory tree expands from a *root* node
    - *fully qualified* names begin from the root
  - may actually form a directed graph

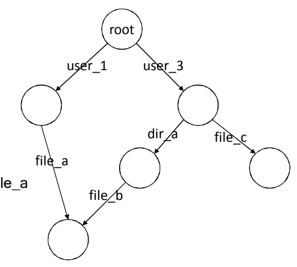
A rooted directory tree



True Names vs. Path Names

- Some file systems have “true names”
- DOS and ISO9660 have a single “path name”
  - files are described by directory entries
  - data is referred to by exactly one directory entry
  - each file has only one (character string) name
- Unix (and Linux) … have named links
  - files are described by I-nodes (w/unique I#)
  - directories associate names with I-node numbers
  - many directory entries can refer to same I-node

Hard Links: example



ln /user_3/dir_a/file_b /user_1/file_a

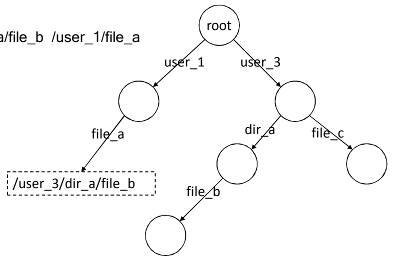
Both names now refer to the same I-node

Unix-style Hard Links

- all protection information is stored in the file
  - file owner sets file protection (e.g. read-only)
  - all links provide the same access to the file
  - anyone with read access to file can create new link
  - but directories are protected files too
    - not everyone has read or search access to every directory
- all links are equal
  - there is nothing special about the owner's link
  - file is not deleted until no links remain to file
  - reference count keeps track of references

Symbolic Links: example

```
ln -s /user_3/dir_a/file_b /user_1/file_a
```



/user_1/file_a is now a macro for /user_3/dir_a/file_b

Symbolic Links

- another type of special file
  - an indirect reference to some other file
  - contents is a path name to another file
- Operating System recognizes symbolic links
  - automatically opens associated file instead
  - if file is inaccessible or non-existent, the open fails
- symbolic link is not a reference to the I-node
  - symbolic links will not prevent deletion
  - do not guarantee ability to follow the specified path
  - Internet URLs are similar to symbolic links

Generalized Directories: Issues

- Can there be multiple links to a single file?
  - who can create new references to a file?
  - if one reference is deleted, does the file go away?
  - can the file's owner cancel other peoples' access?
- Can clients work their way back up the tree?
- Is the namespace truly a tree
  - or is it an a-cyclic directed graph
  - or an arbitrary directed graph
- Does namespace span multiple file systems?

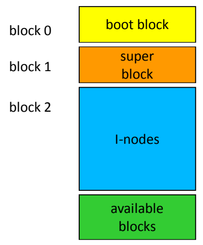
File System Goals

- 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

- disk volumes are divided into 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

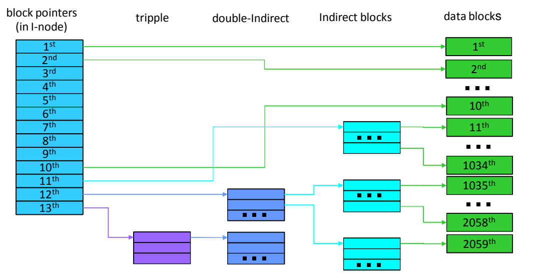
type	protection
owner	group
# links	
file size	
last access time	
last written time	
last I-node update time	
data block pointers …	

- 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



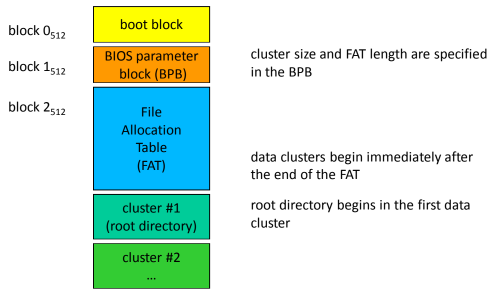
(Unix I-node block mapping)

- 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)

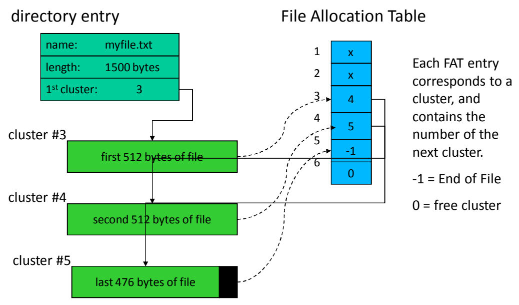
I-nodes – performance

- 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


block 0_{512}
block 1_{512}
block 2_{512}
boot block
BIOS parameter block (BPB)
File Allocation Table (FAT)
cluster #1 (root directory)
cluster #2 …
cluster size and FAT length are specified in the BPB
data clusters begin immediately after the end of the FAT
root directory begins in the first data cluster

Clusters in a DOS FAT File



(DOS FAT File Systems – Overview)

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

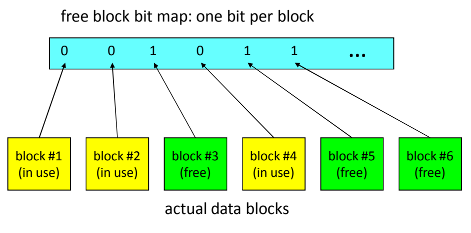
FAT – Performance/Capabilities

- 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

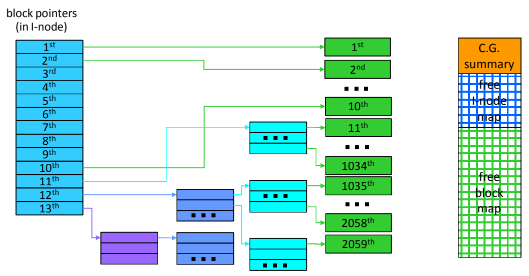


BSD file systems use bit-maps to keep track of both free blocks and free I-nodes in each cylinder group

(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



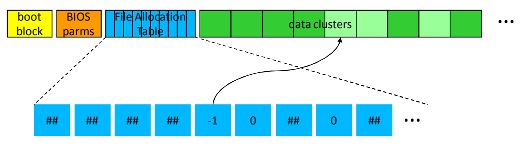
FFS create(/foo/bar)

	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



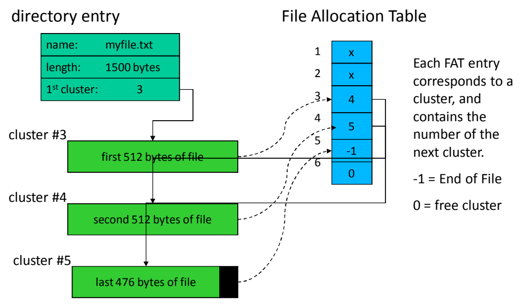
Each FAT entry corresponds to a cluster, and contains the number of the next cluster.

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



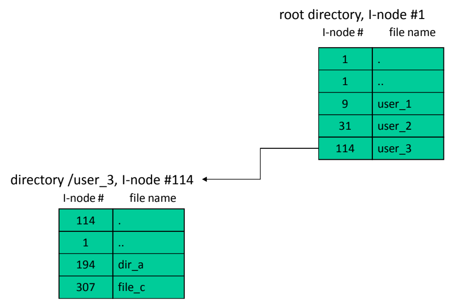
(Extending a DOS/FAT file)

- 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

Directories are usually files

- directories are a special type of file
  - used by OS to map file names into the associated files
- a directory contains multiple directory entries
  - each directory entry describes one file and its name
- user applications are allowed to read directories
  - to get information about each file
  - to find out what files exist
- only Operating System is allowed to write them
  - the file system depends on the integrity of directories

UNIX Directories


root directory, I-node #1

I-node #	file name
1	.
1	..
9	user_1
31	user_2
114	user_3

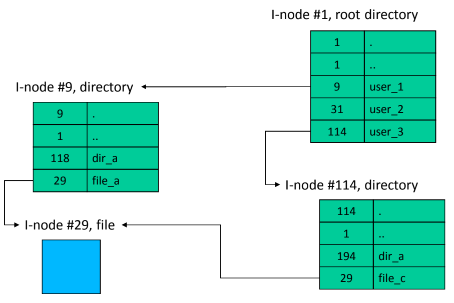
directory /user_3, I-node #114

I-node #	file name
114	.
1	..
194	dir_a
307	file_c

(Example: UNIX Directories)

- file names separated by slashes
  - e.g. /user_3/dir_a/file_b
- the actual file descriptors are the I-nodes
  - directory entries only point to I-nodes
  - association of a name with an I-node is called a "link"
  - multiple directory entries can point to the same I-node
- contents of a Unix directory entry
  - name (relative to this directory)
  - pointer to the I-node of the associated file

Hard Links - example


I-node #1, root directory

1	.
1	..
9	user_1
31	user_2
114	user_3

I-node #9, directory

9	.
1	..
118	dir_a
29	file_a

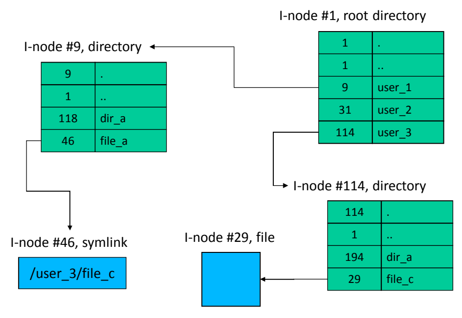
I-node #114, directory

114	.
1	..
194	dir_a
29	file_c

Hard Links and De-allocation

- there can be many links to a single I-node
  - all links are equivalent
  - no link enjoys a preferential (e.g. master) status
- file exists as long as at least one link exists
- most easily implemented w/reference counts
  - increment with every link operation
  - decrement with every unlink operation
  - delete file when reference count goes to zero
- could be implemented with garbage collection

Symbolic Links - example



I-node #1, root directory

1	.
1	..
9	user_1
31	user_2
114	user_3

I-node #9, directory

9	.
1	..
118	dir_a
46	file_a

I-node #114, directory

114	.
1	..
194	dir_a
29	file_c

DOS Directories

root directory, starting in cluster #1

file name	type	length	...	1st cluster
user_1	DIR	256 bytes	...	9
user_2	DIR	512 bytes	...	31
user_3	DIR	284 bytes	...	114

Directory /user_3, starting in cluster #114

file name	type	length	...	1st cluster
..	DIR	256 bytes	...	1
dir_a	DIR	512 bytes	...	62
file_c	FILE	1824 bytes	...	102

(Example: DOS Directories)

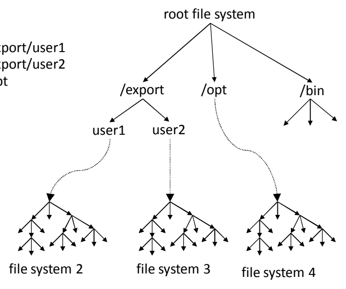
- File & directory names separated by back-slashes
  - e.g. \user_3\dir_a\file_b
- directory entries are the file descriptors
  - as such, only one entry can refer to a particular file
- contents of a DOS directory entry
  - name (relative to this directory)
  - type (ordinary file, directory, ...)
  - location of first cluster of file
  - length of file in bytes
  - other privacy and protection attributes

Unix File System Mounts

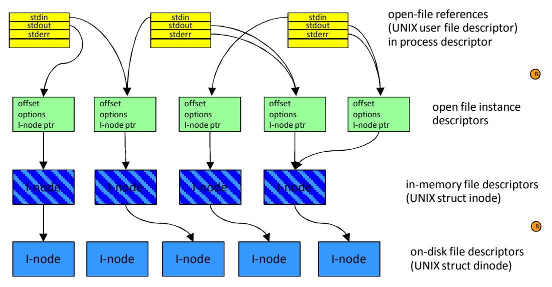
- goal
  - make many file systems appear to be one giant
  - users need not be aware of file system boundaries
- mechanism
  - mount <u>device</u> on <u>directory</u>
  - creates a warp from the named <u>directory</u> to the top of the file system on the specified <u>device</u>
  - any file name beneath that directory is interpreted relative to the root of the mounted file system

Unix - Mounted File Systems

mount filesystem2 on /export/user1
mount filesystem3 on /export/user2
mount filesystem4 on /opt



Open Files – Levels of Indirection


stdin
stdout
stderr
open-file references (UNIX user file descriptor) in process descriptor
offset
options
I-node ptr
open file instance descriptors
I-node
in-memory file descriptors (UNIX struct inode)
on-disk file descriptors (UNIX struct dinode)

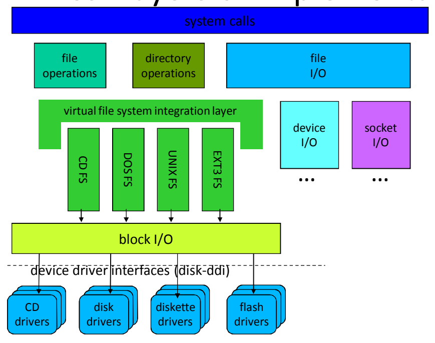
(Open Files – Levels of Indirection)

- open file references (UNIX user file descriptors)
  - array to associate open file index numbers w/files
- open file descriptors (UNIX file structures)
  - describes an open instance (session) of a file
    - current offset, access (read/write), lock status
- in-memory file descriptors (UNIX I-nodes)
  - copy of on-disk file description
- on-disk file descriptors (UNIX dinodes)
  - file description (ownership, protection, etc)
  - location (on disk) of the file's data

File Systems

- file systems implemented on top of block I/O
  - should be independent of underlying devices
- all file systems perform same basic functions
  - map names to files
  - map <file, offset> into <device, block>
  - manage free space and allocate it to files
  - create and destroy files
  - get and set file attributes
  - manipulate the file name space
- different implementations and options

Files: Layers of implementation



Virtual File System (integration) Layer

- federation layer to generalize file systems
  - permits rest of OS to treat all file systems as the same
  - support dynamic addition of new file systems
- plug-in interface or file system implementations
  - DOS FAT, Unix, EXT3, ISO 9660, network, etc.
  - each file system implemented by a plug-in module
  - all implement same basic methods
    - create, delete, open, close, link, unlink,
    - get/put block, get/set attributes, read directory, etc
- implementation is hidden from higher level clients
  - all clients see are the standard methods and properties

Device Independent Block I/O

- simplifying abstraction – better than generic disks
- an LRU buffer cache for disk data
  - hold frequently used data until it is needed again
  - hold pre-fetched read-ahead data until it is requested
- buffers for data re-blocking
  - adapting file system block size to device block size
  - adapting file system block size to user request sizes
- automatic buffer management
  - allocation, deallocation
  - automatic write-back of changed buffers

Assignments

- For next lecture
  - AD 41 FFS Implementation
  - AD 42 Crash Consistency
  - AD 43 Logging File Systems
  - AD 44 Data Integrity
  - AD appx I.6-10 (SSD)
- Lab
  - start on 4C as soon as you finish 4B, server communication and SSL can be hard to debug

Supplementary Slides

Indexed Sequential Files

- record structured files for database like use
  - records may be fixed or variable length
- all records have one or more keys
  - records can be accessed by their key
  - sample key: student ID number
- new file update operations
  - insert record, delete record
- performance challenges
  - efficient insertion, key searches

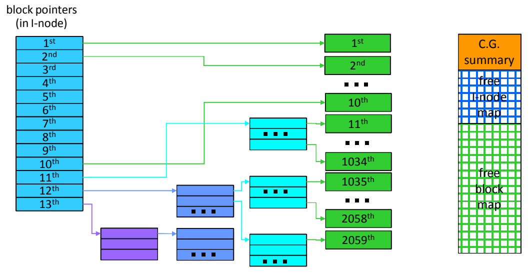
What is an Index

- a table of contents for another file
  - lists keys, and pointers to associated records
  - built by examining the real data file
- enables much faster access to desired records
  - search for records in index rather than file
  - index is much shorter, and sorted by key(s)
- index is sometimes called an inverted file
  - files are accessed by record location, to find the data
  - index is accessed by data key, to find record location

Name Space Structure

- how many files can have the same name?
  - one per file system ... flat name spaces
  - one per directory ... hierarchical name spaces
- how many different names can one file have?
  - a single "true name"
  - only one "true name", but aliases are allowed
  - arbitrarily many
- do different names have different privileges?
  - does deleting one name make others disappear too?
  - do all names see the same access permissions?

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

Block Device Drivers

- generalizing abstraction – make all disks look same
- implement standard operations on their devices
  – asynchronous read (physical block #, buffer, bytecount)
  – asynchronous write (physical block #, buffer, bytecount)
- map logical block numbers to device addresses
  – e.g. logical block number to <cylinder, head, sector>
- encapsulate all the particulars of device support
  – I/O scheduling, initiation, completion, error handlings
  – size and alignment limitations

File Systems and Disks

- independence of multiple disks
  – they can be turned on and off independently
  – they can be backed-up and restored independently
  – some are physically removable (diskette, CD, Flash)
- file system spanning multiple (non RAID) disks is risky
  – losing one disk could lose parts of many files
  – better to lose all of some files and none of others
  – disks can be checked, repaired, restored independently
- people do put multiple file systems on a single disk
  – partitioning a physical disk into multiple logical disks

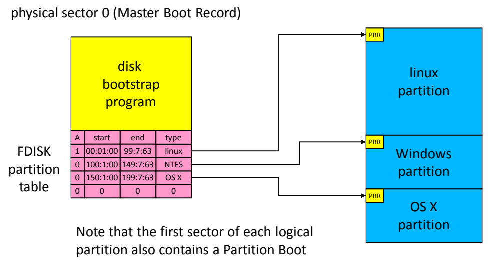
Logical Disk Partitioning

- divide physical disk into multiple logical disks
  – perhaps in disk driver, perhaps through meta-driver
  – rest of system sees partitions as separate devices
- typical motivations
  – permit multiple OS to coexist on a single disk
    - e.g. a notebook that can boot either Windows or Linux
  – fire-walls for installation, back-up and recovery
    - e.g. separate personal files from the installed OS file system
  – fire-walls for free-space
    - running out of space on one file system doesn't affect others

Disk Partitioning Mechanisms

- some designed for use by a particular OS
  – e.g. Linux LVM partitions, understood by GRUB
- some designed to support multiple OS
  – e.g. DOS FDISK partitions, understood by BIOS
- there may be hierarchical partitioning
  – e.g. logical volumes within an FDISK partition
- should be possible to boot from any partition
  – direct from BIOS, or w/help from L2 bootstrap

example: FDISK Disk Partitioning



A	start	end	type
1	00:01:00	99:7:63	linux
0	100:1:00	149:7:63	NTFS
0	150:1:00	199:7:63	OS X
0	0	0	0

Note that the first sector of each logical partition also contains a Partition Boot Record, which will be used to boot the operating system for that partition.

A Simple Bootstrap Procedure

1. BIOS tries designated devices in a configurable order
2. Read MBR (Block 0) from chosen device and check for validity, and branch to it.
3. Scan FDISK table to find ACTIVE partition, read PBR (block 0) from chosen partition, and branch to it.
4. PBR loader finds and loads 2nd level bootstrap (e.g. GRUB), and branches to it.
5. 2nd level bootstrap (often a very sophisticated program) finds and loads operating system.
6. all early-stage loading is done by calls to BIOS

Working with multiple file systems

- finding files is easy if there is only one file system
  - any file we want must be on that one file system
  - directories enable us to name files within a file system
- what if there are multiple file systems available?
  - somehow, we have to say which one our file is on
- how do we specify which file system to use?
  - one way or another, it must be part of the file name
  - it may be implicit (e.g. same as current directory)
  - we need some way of specifying which file system

Specifying Which File System

- we could specify the physical device it resides on
  - e.g. "/devices/pci/pci1000,4/disk/lun1/partition2"
    - that would get old real quick
- we could assign logical names to our partitions
  - e.g. "A:", "C:", "D:"
    - you only have to think physical when you set them up
    - but you still have to be aware multiple volumes exist
- we could weave a multi-file-system name space
  - e.g. Unix mounts