COS 318: Operating Systems

File Structure

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(http://www.cs.princeton.edu/courses/cos318/)

Where Are We?

- Covered:
  - Management of CPU & concurrency
  - Management of main memory & virtual memory
  - Management of I/O devices
- Currently --- File Systems
  - This lecture: File Structure
- Then:
  - Naming and directories
  - Efficiency and performance
  - Reliability and protection

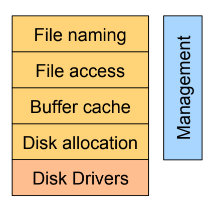
The File System Abstraction

- Open, close, read, write … named files, arranged in folders or directories

Physical Reality	**File System Abstraction**
block oriented	byte oriented (char stream)
physical sector #'s	named files
no protection	users protected from each other
data might be corrupted if machine crashes	robust to machine failures

File System

- Naming
  - File name and directory
- File access
  - Read, write, other operations
- Buffer cache
  - Reduce client/server disk I/Os
- Disk allocation
  - Layout, mapping files to blocks
- Security, protection, reliability, durability
- Management tools



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Topics

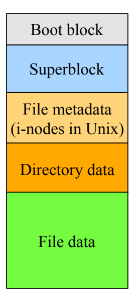
- File system structure
- Disk allocation and i-nodes
- Directory and link implementations
- Physical layout for performance

Typical File Attributes

- **Name**
- **Type** – needed for systems that support different types
- **Location** – pointer to file location on device.
- **Size** – current file size.
- **Protection** – controls who can read, write, execute
- **Time**, **date**, **and user identification** – data for protection, security, and usage monitoring
- Information about files are kept in the directory structure, which is maintained on the disk

Typical Layout of a Disk Partition

- Boot block
  - Code to load and boot OS
- Super-block defines a file system
  - File system info: type, no of blocks, ...
  - File metadata area
  - Information about / ptr to free blocks
  - Location of descriptor of root directory
- File metadata
  - Each descriptor describes a file
- Directories
  - Directory data (directory and file names)
- File data
  - Data blocks



File Types – Name, Extension

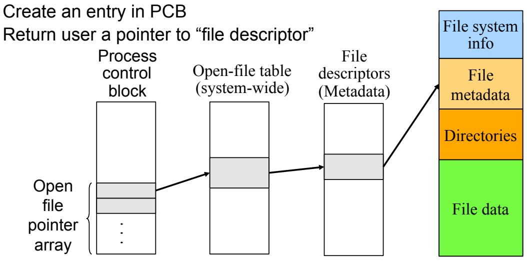
File Type	Usual extension	Function
Executable	exe, com, bin or none	ready-to-run machine-language program
Object	obj, o	complied, machine language, not linked
Source code	c, p, pas, 177, asm, a	source code in various languages
Batch	bat, sh	commands to the command interpreter
Text	txt, doc	textual data documents
Word processor	wp, tex, rrf, etc.	various word-processor formats
Library	lib, a	libraries of routines
Print or view	ps, dvi, gif	ASCII or binary file
Archive	arc, zip, tar	related files grouped into one file, sometimes compressed.

Typical File Operations

- Create
- Write
- Read
- Reposition within file – file seek
- Delete
- Truncate
- Open(F_i) – search the directory structure on disk for entry F_i, and move the content of entry to memory.
- Close (F_i) – move the content of entry F_i in memory to directory structure on disk.

Open A File: Open(fd, name, access)

- Various checking (directory and file name lookup, authenticate)
- Copy the file descriptors into the in-memory data structure
- Create an entry in the open file table (system wide)
- Create an entry in PCB
- Return user a pointer to "file descriptor"



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Translating from user to system view

- User wants to read 10 bytes from file starting at byte 2?
  - Seek byte 2, fetch the block, read 10 bytes
- User wants to write 10 bytes to file starting at byte 2?
  - Seek byte 2, fetch the block, write 10 bytes, write out block
- Everything inside file system is in whole size blocks
  - Even getc and putc buffers 4096 bytes
- From now on, file is collection of blocks.

File system design constraints

- For small files:
  - Small blocks for storage efficiency
  - Files used together should be stored together
- For large files:
  - Contiguous allocation for sequential access
  - Efficient lookup for random access
- May not know at file creation whether file will become small or large

File usage patterns

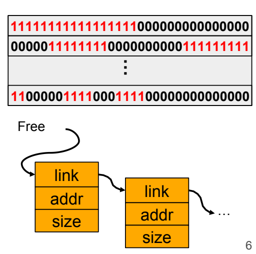
- How do users access files?
  - Sequential: bytes read in order
  - Random: read/write element out of middle of arrays
  - Content-based access: find me next byte starting with "COS318"
- How are files used?
  - Most files are small
  - Large files use up most of the disk space
  - Most transfers are small
  - Large files account for most of the bytes transferred
- Bad news
  - Need everything to be efficient

File system design

- Data structures
  - Directories: file name -> file metadata
    - Store directories as files
  - File metadata: used to find file data blocks
  - Free map: list of free disk blocks
- How do we organize these data structures?

Data Structures for Storage Allocation

- A File
  - Metadata
  - A list of data blocks
- Free space data structure
  - Bit map indicating the status of disk blocks
  - Linked list that chains free blocks together
  - Buddy system
  - …
- Let's look at some ways of keeping track of file data



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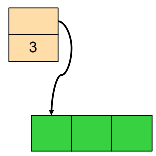
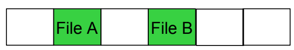
Data structures for disk management

- A file header for each file (part of the file meta-data)
  - Disk sectors associated with each file
- A data structure to track free space on disk
  - Bit map
    - 1 bit per block (sector)
    - blocks numbered in cylinder-major order, why?
  - Linked list
  - Others?
- What about allocation for the blocks associated with a file?

Contiguous Allocation

- Allocate contiguous blocks on storage
  - Bitmap: find N contiguous 0's
  - Linked list: find a region (size >= N)
- File metadata
  - First block in file
  - Number of blocks
- Pros
  - Fast sequential access
  - Easy random access
- Cons
  - External fragmentation (what if file C needs 4 blocks)
  - Hard to grow files





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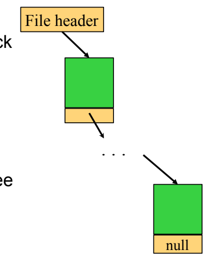
Linked Files

- File structure (Alto)
  - File metadata points to 1st block on storage
  - A block points to the next
  - Last block has a NULL pointer
- Pros
  - Can grow files dynamically
  - File data tracked similarly to free list of blocks
  - Doesn't waste space
- Cons
  - Random access: bad
  - Unreliable: losing a block means losing the rest



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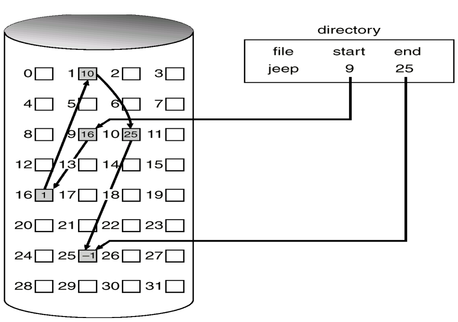
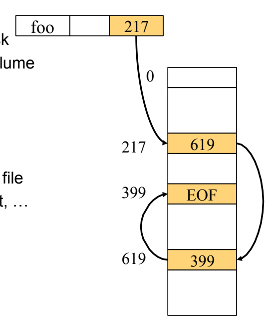
Linked files (cont'd)



File Allocation Table (FAT)

- Idea is to keep the linked list metadata (pointers) in memory, rather than on disk
- Allocation table at beginning of each volume
  - N entries for N blocks
  - Want to keep it in memory
- File structure (MS-DOS)
  - A file is a linked list of blocks
  - File metadata points to first block of file
  - The entry of first block points to next, …
- Pros
  - Simple
- Cons
  - Random access: still not good
  - Wastes space - table for each file expensive to keep in memory



FAT Allocation Table

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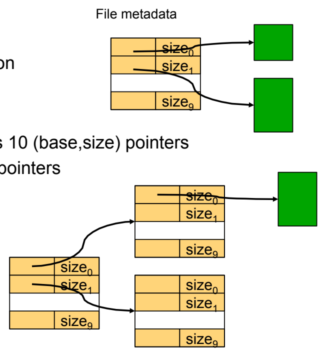
DEMOS (Cray-1)

- Idea
  - Try contiguous allocation
  - Allow non-contiguous
- File structure
  - Small file metadata has 10 (base,size) pointers
  - Big file has 10 indirect pointers
- Pros & Cons
  - Can grow (max 10GB)
  - Fragmentation



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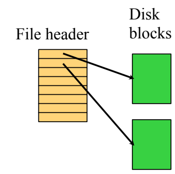
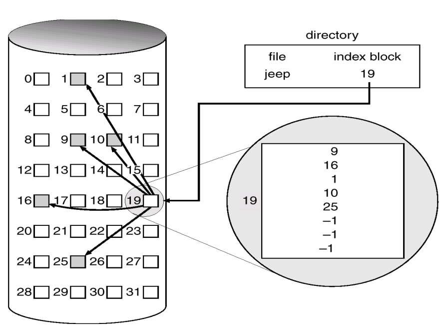
Single-level Indexed File

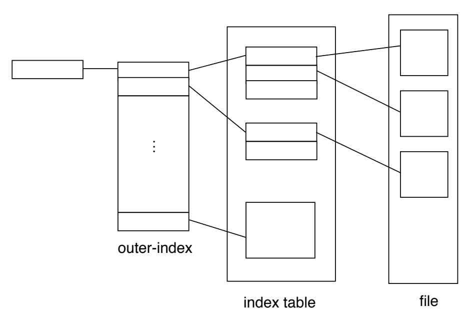
- User declares max size
- File header holds array of pointers to disk blocks
- Pros:
  - Can grow up to a limit
  - Random access is fast
  - No external fragmentation
- Cons:
  - Clumsy to grow beyond limit
  - Still lots of seeks



Single-level indexed files (cont'd)

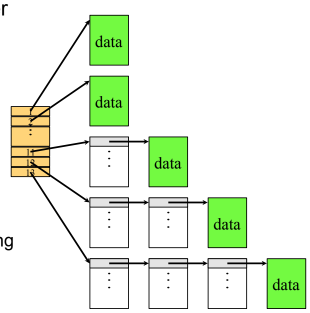


Multi-level Indexed Files



Hybrid Multi-level Indexed Files (Unix)

- 13 Pointers in a header
  - 10 direct pointers
  - 11: 1-level indirect
  - 12: 2-level indirect
  - 13: 3-level indirect
- Pros & Cons
  - In favor of small files
  - Can grow
  - Limit is 16G
  - Can have lots of seeking



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Original Unix i-node

- Mode: file type, protection bits, setuid, setgid bits
- Link count: no. of directory entries pointing to this file
- Uid: uid of the file owner
- Gid: gid of the file owner
- File size
- Times (access, modify, change)

- 10 pointers to data blocks
- Single indirect pointer
- Double indirect pointer
- Triple indirect pointer

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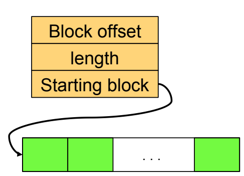
Extents

- An extent is a variable number of blocks
- Main idea
  - A file is a number of extents
  - XFS uses 8Kbyte blocks
  - Max extent size is 2M blocks
- Index nodes need to have
  - Block offset
  - Length
  - Starting block
- Microsoft NTFS, Linux EXT4, …
- Pros: little metadata, fast seq access, can grow over time, less fragmentation
- Cons: external fragmentation still problem



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Naming Files

Can name files via:

- Index (i-node number): Not easy for users to specify
- Text name: Need to map it to index
- Icon: Need to map it to index or to text and then to index

- Directories
  - Table of file name, file index pairs
  - Map name to file index (where to find the header)
  - A directory is itself stored as a file

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Naming Tricks

- Bootstrapping: Where do you start looking?
  - Root directory
  - inode #2 on the system
  - 0 and 1 used for other purposes
- Special names:
  - Root directory: "/" (bootstrap name system for users)
  - Current directory: "."
  - Parent directory: ".." (otherwise how to go up??)
  - user's home directory: "~"
- Using the given names, only need two operations to navigate the entire name space:
  - cd 'name': move into (change context to) directory "name"
  - ls : enumerate all names in current directory (context)

Directory Organization Examples

- Flat (CP/M)
  - All files are in one directory
- Hierarchical (Unix)
  - /u/cos318/foo
  - Directory is stored in a file containing (name, i-node) pairs
  - The name can be either a file or a directory
- Hierarchical (Windows)
  - C:\windows\temp\foo
  - File extensions have meaning (unlike in Unix). Use the extension to indicate whether the entry is a directory

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Mapping File Names to i-nodes

Need to support the following types of operations:

- Create/delete
  - Create/delete a directory
- Open/close
  - Open/close a directory for read and write
- Link/unlink
  - Link/unlink a file
- Rename
  - Rename the directory

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Linear List

- Method
  - <FileName, i-node> pairs are linearly stored in a file
  - Create a file
    - Append <FileName, i-node>
  - Delete a file
    - Search for FileName
    - Remove its pair from the directory
    - Compact by moving the rest
- Pros
  - Space efficient
- Cons
  - Linear search
  - Need to deal with fragmentation

/u/jps
foo bar …
veryLongFileName

<foo,1234> <bar, 1235> … <very LongFileName, 4567>

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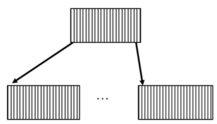
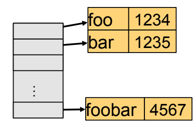
Tree Data Structure

- Method
  - Store <fileName, i-node> a tree data structure such as B-tree
  - Create/delete/search in the tree data structure
- Pros
  - Good for a large number of files
- Cons
  - Inefficient for a small number of files
  - More space
  - Complex



Hashing

- Method
  - Use a hash table to map FileName to i-node
  - Space for name and metadata is variable sized
  - Create/delete will trigger space allocation and free
- Pros
  - Fast searching and relatively simple
- Cons
  - Not as efficient as trees for very large directory (wasting space for the hash table)

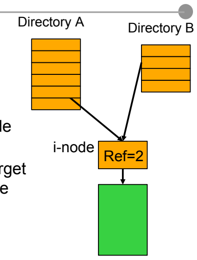


Number of I/O operations

- I/Os to access a byte of /u/cos318/foo
  - Read the i-node and first data block of "/"
  - Read the i-node and first data block of "u"
  - Read the i-node and first data block of "cos318"
  - Read the i-node and first data block of "foo"
- I/Os to write a file
  - Read the i-node of the directory and the directory file (as above)
  - Read or create the i-node of the file
  - Read or create the file itself
  - Write back the directory and the file
- Too many I/Os to traverse the directory
  - Solution is to use ***Current Working Directory*** (e.g. ./foo)

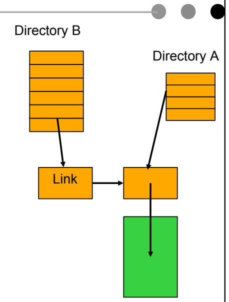
Hard Links

- Approach
  - A link to a file with the same i-node
    `ln source target`
  - i.e. the name points to the same i-node as that of the file being linked to
  - Delete may or may not remove the target depending on whether it is the last one (link reference count)
- Main issue with hard links?



Symbolic Links

- Approach
  - A symbolic link is a pointer to a file
  - Use a new i-node for the link
    `ln –s source target`
  - Carries pathname of original file
- Main issue with symbolic links?
  - Performance?
  - What if you delete the link?
  - What if you delete the original file?



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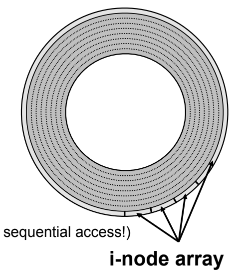
Original Unix File System Disk Layout

- Simple disk layout
  - Block size is sector size (512 bytes)
  - i-nodes are on outermost cylinders
  - Data blocks are on inner cylinders
  - Use linked list for free blocks
- Issues
  - Index is large
  - Fixed max number of files
  - i-nodes far from data blocks
  - i-nodes for directory not close together
  - Consecutive blocks can be anywhere
  - Poor bandwidth (20Kbytes/sec even for sequential access!)



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BSD FFS (Fast File System)

- Use a larger block size: 4KB or 8KB
  - Allow large blocks to be chopped into fragments
  - Used for small files and pieces at ends of files
- Use bitmap instead of a free list
  - Try to allocate contiguously

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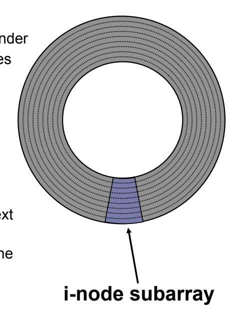
FFS Disk Layout

- i-nodes are grouped together
  - A portion of the i-node array on each cylinder
  - In same cylinder group as data for the files
  - 10% reserved disk space, to keep room
- Do you ever read i-nodes without reading any file blocks?
  - 4 times more often than reading together
  - examples: ls, make
- Overcome rotational delays
  - Skip sector positioning to avoid the context switch delay
  - Read ahead: read next block right after the first



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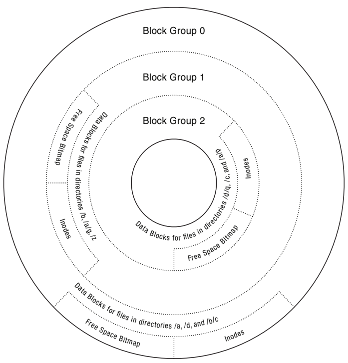
FFS block groups for better locality



What Has FFS Achieved?

- Performance improvements
  - 20-40% of disk bandwidth for large files (10-20x original)
  - Better small file performance (why?)
- We can do better
  - Extent based instead of block based
    - Use a pointer and size for all contiguous blocks (XFS, Veritas file system, etc)
  - Synchronous metadata writes hurt small file performance

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Summary

- File system structure
  - Boot block, super block, file metadata, file data
- File metadata
  - Consider efficiency, space and fragmentation
- Directories
  - Consider the number of files
- Links
  - Soft vs. hard
- Physical layout
  - Where to put metadata and data

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