CS 370: OPERATING SYSTEMS
[FILE SYSTEMS]

"As we board the aircraft, I'd like to remind everyone that your primary storage space is in your cheeks."
Cartoon by Kate Isenberg
New Yorker. November 2, 2023

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Frequently asked questions from the previous class survey

- Does each guest OS on a VM still need as much memory as a regular OS to run?
- Virtual appliance example? SaaS
- Are VMs safer if you someone is doing research on viruses?
- Have systems used ring-2?
- Does the hypervisor try to rewrite instructions other than sensitive, privileged instructions?
  - Why do those instructions still exist?
- Do the VMs have dedicated cores?

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Topics covered in this lecture

- File System Structure
- File System Implementation
- Allocations
  - Contiguous allocation

Memory is the treasury and guardian of all things.
— Marcus Tullius Cicero

FILE SYSTEMS

Rationale #1: Applications need to store and retrieve information

- A program can store a **limited** amount of information in its own address space
- Storage capacity is **restricted** to the size of virtual memory
  - Far too small for several applications
    - Airline reservations, banking, directory services etc

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Rationale #2: Information in the address space of a process is not persistent

- When process terminates, information is lost
- For many applications, information must be **retained** for a much longer time
  - Weeks, Years, Forever

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Rationale #3: Multiple processes often need to access (parts of) information at the same time

- Storing an online telephone directory in the address space of one process?
  - Only that process can access the info
  - Only one telephone number can be looked up at a time

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Essential requirements for long-term storage

① **Store** a very large amount of information

② Information must **survive** process termination

③ Multiple processes must be able to **concurrently access** the information

- Store information on disk or external media
  - In units called **files**

- If you printed 1 TB of data as text on paper, you would produce a stack about 20 miles high.

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Files are an abstraction mechanism

- Provide a way to store information and read it back later
- Do this is in a way that **shields** the user from
  - How and where information is stored on disk
  - How disks really work

Naming files

- Important characteristic of the abstraction mechanism
- Data must be shared across programs
  - Storage systems must provide ways to easily identify data of interest
- Strings 8-255 characters long
- Most OS support two-part file names separated by a period
  - Last part referred to as the **file extension**
    - Conventions: Easy to remember
    - Enforced in some cases e.g., the compiler

Files can be structured in many ways: Unstructured sequence of bytes

- The OS does not know or care what is in the file
  - Maximum **flexibility**
- OS does not help, but does not get in the way either
- Meaning is imposed by programs
- Most OS support this

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File Structure: A sequence of records

- A file is a sequence of **fixed-length** records
- Read operation returns one record
  - Write operation overwrites/appends one record
- 80-column punch card used to be dominant
  - Files consisted of 80 character records

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Directory and disk structure

- Typically, there are millions of files within a computer
- Storage device can be used in its entirety for a file system
- It could also be **partitioned**
  - Limit size of individual file systems
  - Put multiple file system types
  - Set aside for **swap space**

Directories are used to organize files

- Can be viewed as a **symbol table**
- In many systems, directories themselves are files
- Supported operations
  1. Insert, delete, search, list and rename entries
  2. Traversal

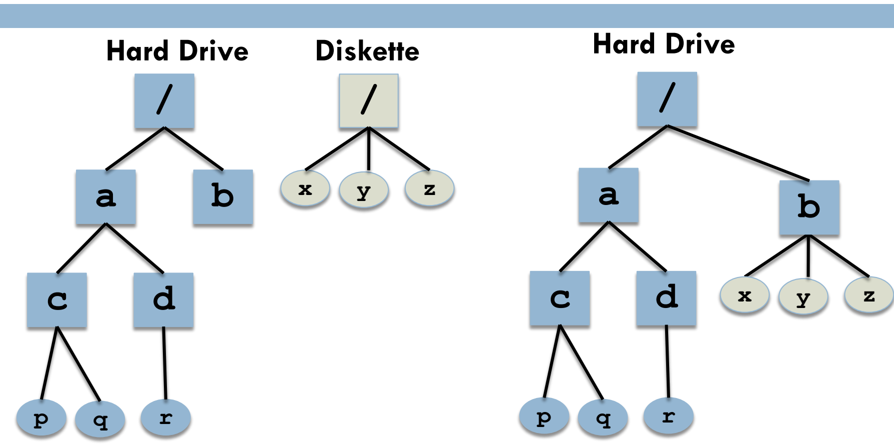
Organization of directories

- Single level directory
- Two-level directory
- Tree-structured directories
- Acyclic graph directories
  - Shared sub-directory

Mounting file systems

- Many systems have more than one disk
  - How do you handle them?
- **S1**: Keep self-contained file system on each disk
  - And keep them separate
- **S2**: Allow one disk to be **mounted** in another disk's file tree

Mounting file systems



`cp D:/x /a/d/x`
H is default

`cp /b/x /a/d/x`

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Checks performed during mounting

- OS **verifies** that the device contains a valid file system
- Read device directory
  - Make sure that the format is an expected one
- Windows mounting
  - Each device in a separate name space
  - {Letter followed by a colon e.g. **G:**}

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Nonvolatile storage and file systems

- Technologies such as magnetic disks and high-density flash **do not allow** random access to individual words of storage
  - Instead, access must be done in coarser-grained units — 512, 2048, or more bytes at a time
- Furthermore, these accesses can be much slower than access to DRAM (5-6 orders of magnitude)
- This large difference drives the OS to organize and use persistent storage devices differently than main memory

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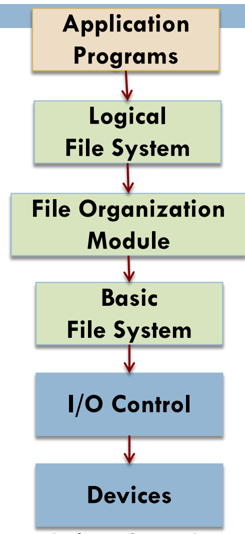
Disks provide the bulk of secondary storage

- A disk can be **rewritten** in place
  - Read, modify, and then write-back to same place
- Disks can **directly access** any block of information
- I/O transfers between memory and disk are performed in units of **blocks**

There are two core design problems in file systems

- Defining how the file system should **look** to the user
- Creating algorithms and data structures to **map** logical file system onto physical storage

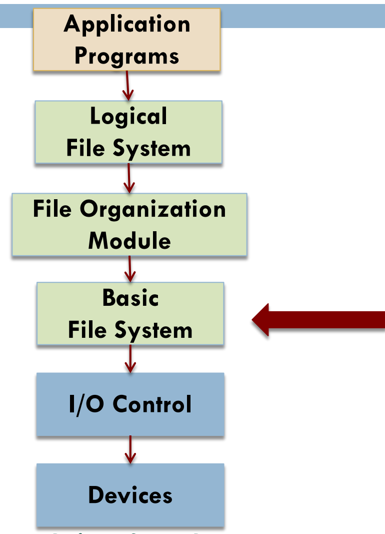
There are many levels that comprise a file system



I/O Control consists of device drivers

- Transfers information *between main memory and disk*
- Receives **high-level** commands
  - Retrieve block 123, etc
- Outputs low-level, hardware-specific instructions
  - Used by the hardware controller
  - Writes bit patterns into specific locations of the I/O controller

There are many levels that comprise a file system



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Basic file system issues commands to the device driver

- Read and write physical blocks on disk
  - E.g.: Drive 1, cylinder 73, sector 10
- Manages **buffers and caches**
  1. To hold file system, directory and data blocks
  2. Improves performance

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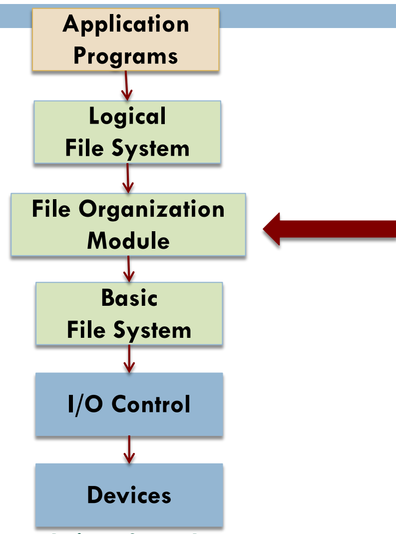
There are many levels that comprise a file system



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File organization module

- Knows about files
  - Logical and physical blocks
- **Translate** logical addresses to physical ones
  - Needed for every block
- Includes a **free space manager**
  - Tracks unallocated blocks and allocates as needed

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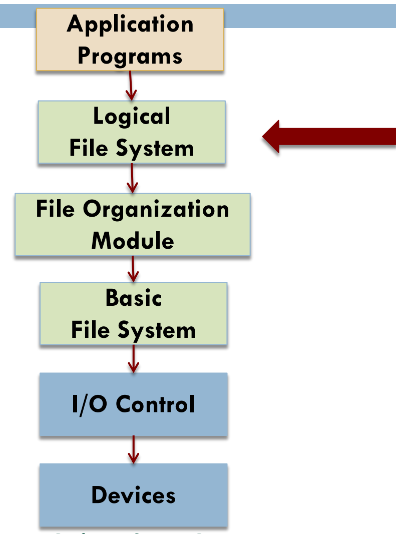
There are many levels that comprise a file system



The logical file system

- Manages **metadata** information
  - Metadata is *data describing the data*
- Maintains file structure via **file control blocks**
  - Info about the file
    - Ownership and permissions
    - Location of file contents
  - **inode** in UNIX file systems

Several file systems are in use

- CD-ROMs written in ISO 9660 format
  - Designed by CD manufacturers
- UNIX
  - Unix file system (**UFS**)
  - Berkley Fast File System (**FFS**)
- Windows: **FAT, FAT32** and **NTFS**
- Linux
  - Supports 40 different file systems
  - Extended file system: **ext2, ext3** and **ext4**

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Using a magnet and a nail for instant messaging? [1/2]

- **Message**: See you later; or not
- Drop a nail in your friend's mailbox
  - If nail is magnetized? You'll see the friend
  - If nail is not magnetized? You won't

Using a magnet and a nail for instant messaging? [2/2]

- Your friend comes home and picks up the nail
  - Uses the nail to pick up a paper-clip
    - If it sticks? Friend will expect to see you
- Magnetism can be used to store information!

Using magnetism to store information

- Store information even when you turn power off!
- Storing …**10001**…?
  - Magnetize first bit
  - Demagnetize next 3
  - Magnetize the next bit

The anatomy of a disk

- A disk comprises a set of **platters**
  - These have a flat, circular shape
  - Usually made of glass or aluminum
- Both surfaces of a platter covered with **magnetic material**
  - Store information by recording it magnetically
- A platter is logically divided into circular **tracks**
  - These are subdivided into **sectors**

Rates and times associated with disks

- Rate of data movement between the disk and the memory
  - **Transfer rate**
- Positioning time
  - **Seek time**
    - Move disk arm to the necessary cylinder
  - **Rotational latency**
    - Time for the desired sector to rotate to the disk head

How about CD-ROMs, DVDs, and Blu-Rays? [1/2]

- Data written with the help of *high intensity* laser that makes "**pits**" on the reflecting surface
- During reads:
  - Use a lower intensity laser
  - Mirrors and a focusing lens are used to shine light on a specific portion of the disk
  - The amount of light that is *reflected back* depends on the presence or absence of a pit
    - Use this to interpret a 1 or 0

How about CD-ROMs, DVDs, and Blu-Rays? [2/2]

- The *shorter* the wavelength, the *smaller* the pit
  - And greater the density of what can be stored
- DVD uses a 650 nm wavelength laser diode
  - 780 nm for CD
  - Pit sizes: DVD = 0.74 µm and CD = 1.6 µm
- What about Blu-Ray?
  - 405 nm wavelength, 0.13 µm pit size
  - 50 GB storage possible on one disk
- What's next?
  - Archival Disc (Sony/Panasonic) 79.5 nm with 300 GB of data storage

A pen--to register; a key--
That winds through secret wards
Are well assigned to Memory
By allegoric Bards.

— Memory, William Wordsworth

FILE SYSTEM IMPLEMENTATION

On-disk structures used to implement a file system [1/2]

- **Boot control block**
  - Information needed to boot an OS from that volume
- **Volume control block**: Volume information
  - Number of blocks in the partition
  - Size of the blocks
  - Free-block count/pointers
  - Free file-control-block count/pointers
  - UFS: **super-block** Windows: **Master file table**

On-disk structures used to implement a file system [2/2]

- Directory structure to organize files
  - One per file system
- Per file file-control-block
  - Contains details about individual files

In memory structures used to improve performance via caching

- **Mount** table
  - Information about each mounted volume
- Directory structure **cache**
  - Holds information about recently accessed directories
- System-wide **open file** table
  - File control block of each open file
- **Buffers** to hold file-system blocks
  - To read and write to storage

Creation of a new file

- **Allocate** a file-control block (FCB)
- Read appropriate directory into memory
  - Directory is just a file in UNIX
    - Special **type** field
- **Update** directory with new file name and FCB
- Write directory back to disk

Partitions: A disk can be sliced into multiple partitions

- **Cooked**
  - Has a file system
- **Raw**
  - No file system
  - UNIX swap space uses this
  - Hold information needed by disk RAID (***R**edundant **A**rray of **I**ndependent **D**isks*) systems

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Boot information can be stored in a separate partition

- Usually a **sequential** series of blocks
  - Loaded as an image into memory
- Image execution starts at a predefined location

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DIRECTORY IMPLEMENTATION

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Directory Implementation

- Linear List
- Hash Table

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Directory Implementation
Linear List

- File names with pointers to data blocks
- Simple to program
  - Inefficient and slow execution
- Finding a file requires a **linear search**
- Sorted list
  - Complicates creation and deletion
- Tree data structures might help here: B-Tree
- Linux's ext file system uses HTree

Directory implementation:
Hash table

- Linear list **and** a hash table is maintained
- Key computed from file name
  - Hash table value returns pointer to entry in linear list
- Things to consider
  1. Account for **collisions** in the hash space
  2. Need to **rehash** the hash table when the number of entries exceed the limit

Allocation methods: Objective and approaches

- How to allocate space for files such that:
  - Disk space is utilized effectively
  - File is accessed **quickly**
- Major Methods
  - Contiguous
  - Linked
  - Indexed

What's in a name? That which we call a rose
By any other name would smell as sweet.

—Juliet
Romeo and Juliet (II, ii, 1-2)
(Shakespeare)

NOMENCLATURE

Terminology

- Storage hardware arranges data in **sectors** (for magnetic disk) or **pages** (for flash)
- File systems often group together a *fixed number* of disk sectors or flash pages into a larger allocation unit called a **block**.
  - E.g.: format file system to run on a disk with 512b sectors to use 4 KB blocks
- Windows FAT and NTFS refer to blocks as clusters
- **File Control Block** (FCBs) organize info about blocks comprising a file
  - iNode in UFS and MFT Record in NTFS; Master File Table (MFT)

CONTIGUOUS ALLOCATIONS

Contiguous Allocation

- Each file occupies a set of contiguous blocks on the disk
  - If file is of size **n** blocks and starts at location **b**
    - Occupies blocks **b**, **b+1**, …, **b+n-1**
- Disk head movements
  - None for moving from block **b** to (**b+1**)
  - Only when moving to a different track

Sequential and direct access in contiguous allocations

- Sequential accesses
  - Remember *disk address* of the last referenced block
  - When needed, read the next block
- **Direct access** to block **i** of file that starts at block **b**

  b + i

Contiguous allocations suffer from external fragmentation

- Free space is broken up into chunks
  - Space is **fragmented**
- Largest continuous chunk may be insufficient for meeting request
- **Compaction** is very slow on large disks
  - Needs several hours

Determining how much space is needed for a file is another problem

- **Preallocate** if eventual size of file is known?
  - Inefficient if file grows very slowly
    - Much of the allocated space is unused for a long time
- Modified contiguous allocation scheme
  - Allocate space in a continuous chunk initially
  - When space runs out allocate another set of chunks (**extent**)

The contents of this slide-set are based on the following references

- *Avi Silberschatz, Peter Galvin, Greg Gagne. Operating Systems Concepts, 9th edition. John Wiley & Sons, Inc. ISBN-13: 978-1118063330.* [Chapter 4]
- *Thomas Anderson and Michael Dahlin. Operating Systems Principles and Practice. 2nd Edition. Recursive Books. ISBN: 978-0985673529.* [Chapter 11]
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- *Kay Robbins & Steve Robbins. Unix Systems Programming, 2nd edition, Prentice Hall ISBN-13: 978-0-13-042411-2.* [Chapter 4]
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