Lecture 15: File Systems

601.418/618 Operating Systems

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Agenda

- File system concepts
- File system operations
- Protection

Acknowledgments: These slides are shamelessly adapted from Prof. Ryan Huang's Fall 2022 slides, which in turn are based on Prof. David Mazières's OS lecture notes.

File System Fun

File systems: a challenging OS design topic

- More papers on FSes than any other single topic

Main tasks of file system:

- Don't go away (ever)
- Associate bytes with name (files)
- Associate names with each other (directories)
- Can implement file systems on disk, over network, in memory, in non-volatile ram (NVRAM), on tape, w/ paper.
- We'll focus on disk and generalize later

Today: files, directories

Files

File: named bytes on disk

- data with some properties
- contents, size, owner, last read/write time, protection, etc.

How is a file's data managed by the file system?

- Next lecture's topic
- Basic idea (in Unix): a struct called an *index node* or *inode*
  - **Describes where on the disk the blocks for a file are placed**
  - Disk stores an array of inodes, inode # is the index in this array

File Types

A file can also have a type

- Understood by the file system and kernel
  - Block, character, device, portal, link, named pipe, etc.
- Understood by other parts of the OS or runtime libraries
  - Executable, dll, source, object, text, etc.

A file's type can be encoded in its name or contents

- In name: usually, as a "filename extension" (`.com`, `.exe`, `.bat`, `.sh`, `.dll`, `.so`, `.jpg`, `.png`, etc.)
- In contents: magic numbers, initial characters, e.g., #! for shell scripts, etc.

Basic File Operations

Unix	Windows
create(name)	CreateFile(name, CREATE)
open(name, how)	CreateFile(name, OPEN)
read(fd, buf, len)	ReadFile(handle, ...)
write(fd, buf, len)	WriteFile(handle, ...)
sync(fd)	FlushFileBuffers(handle, ...)
seek(fd, pos)	SetFilePointer(handle, ...)
close(fd)	CloseHandle(handle, ...)
unlink(name)	DeleteFile(name)
sendfile(outfd, infd, offset, count)*	CopyFile(fromname, toname)
rename(fromname, toname)*	MoveFile(fromname, toname)

* Linux-only

File Access Methods

FS usually provides different file access methods:

- *Sequential access*
  - read bytes one at a time, in order
  - by far the most common mode
- *Random access*
  - random access given block/byte number
- *Record access*
  - file is array of fixed- or variable-length records
  - read/written sequentially or randomly by record #
- *Indexed access*
  - file system contains an index to a particular field of each record in a file
  - reads specify a value for that field and the system finds the record via the index

What file access method does Unix, Windows provide?

Directories

Problem: referencing files

Users remember where on disk their files are (disk sector no.)?

- E.g., like remembering your social security or bank account #

People want human digestible names

Directories serve two purposes

- For users, they provide a structured way to organize files
- For FS, they provide a convenient naming interface that allows the separation of logical file organization from physical file placement on the disk

A Short History of Directories

Approach 1: Single directory for entire system

- Put directory at known disk location. **If one user uses a name, no one else can.**
- Many ancient personal computers work this way (CP/M, MSDOS 1.0)

Approach 2: Single directory for each user

- Still clumsy, and running `ls` on 10,000 files is a real pain
- Seen in early time-sharing systems (CTSS, ITS)

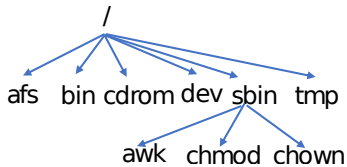
Approach 3: Hierarchical name spaces

- Allow directory to map names to files or other dirs
- File system forms a tree (or graph, if links allowed)

Hierarchical Directory

Used since Multics (1960s)

- Unix picked up and used really nicely



Large name spaces tend to be hierarchical

- ip addresses, domain names, scoping in programming languages, API endpoints in web services, etc.

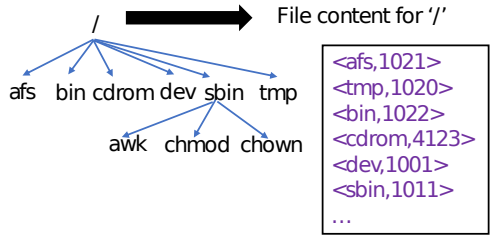
Directory Internals

A directory is a list of entries

- <*name*, *location*> tuple, *location* is typically the inode # (more next lecture)
- An inode describes where on the disk the blocks for a file are placed

Directories stored on disk just like regular files

- File type set to directory
- Users can read just like any other file
- Only special syscalls can write (why?) or read
- File pointed to by the location may be another dir
- Makes FS into hierarchical tree



Simple, plus speeding up file ops speeds up dir ops!

Path Name Translation

Let's say you want to open "/one/two/three"

What does the file system do?

- Directory entries map file names to location (inode #)
- Open directory "/": Where? **Root directory is always inode #2**
- Search for the entry "one", get location of "one" (in dir entry)
- Open directory "one", search for "two", get location of "two"
- Open directory "two", search for "three", get location of "three"
- Open file "three"

Naming Magic

Bootstrapping: Where do you start looking?

- **Root directory always inode #2** (0 and 1 historically reserved)

Special names:

- Root directory: "/"
- Current directory: "."
- Parent directory: ".."

Some special names are provided by shell, not FS:

- User's home directory: "~"
- Globbing: "foo.*" expands to all files starting "foo."

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)

Basic Directory Operations

Unix

Some operations shared for files and directories, some are directory-only or file-only

- `mkdir(name)` (create dir)
- `create(name)` (create file)
- `unlink(name)` (del file or dir)
- `open(name, flags)` (open file or dir)

C library provides a higher-level abstraction for reading directories

- opendir(name)
- readdir(DIR)
- seekdir(DIR)
- closedir(DIR)

Windows

Explicit directory operations

- CreateDirectory(name)
- RemoveDirectory(name)

Very different method for reading directory entries

- FindFirstFile(pattern)
- FindNextFile()

Default Context: Working Directory

Cumbersome to constantly specify full path names

- In Unix, each process has a "current working directory" (cwd)
- File names not beginning with "/" are assumed to be relative to cwd; otherwise translation happens as before

Shells track a default list of active contexts

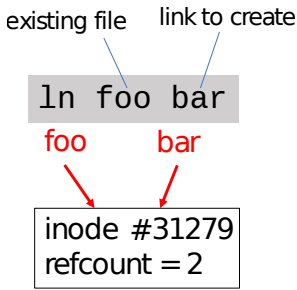
- A "search path" for programs you run
- Given a search path A:B:C, the shell will check in A, then B, then C
- Can escape using explicit paths: "./foo"

Example of locality

Hard Links

More than one dir entry can refer to a given file

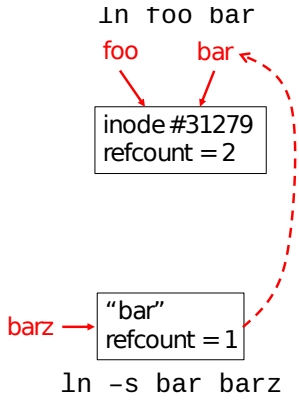
- Hard link creates a synonym for file (but not allowed for directory!)
- Unix stores count of pointers ("hard links") to inode
- If one of the links is removed (e.g., rm), the data are still accessible through any other link that remains
- If all links are removed, the space occupied by the data is freed.



Soft Links

Soft/symbolic links = synonyms for names

- Point to a file/dir name, but object can be deleted from underneath it (or never exist).
- Unix implements like directories: inode has special "symlink" bit set and contains name of link target
- When the file system encounters a soft link it automatically translates it (if possible).



File Sharing

File sharing has been around since timesharing

- Easy to do on a single machine
- PCs, workstations, and networks get us there (mostly)

File sharing is important for getting work done

- Basis for communication and synchronization

Two key issues when sharing files

- Semantics of concurrent access
  - What happens when one process reads while another writes?
  - What happens when two processes open a file for writing?
  - **What are we going to use to coordinate?**
- Protection

Protection

File systems implement a protection system

- Who can access a file
- How they can access it

More generally. . .

- Objects are “what”, subjects are “who”, actions are “how”

A protection system dictates whether a given action performed by a given subject on a given object should be allowed

- You can read and/or write your files, but others cannot
- You can read “`/etc/motd`”, but you cannot write it

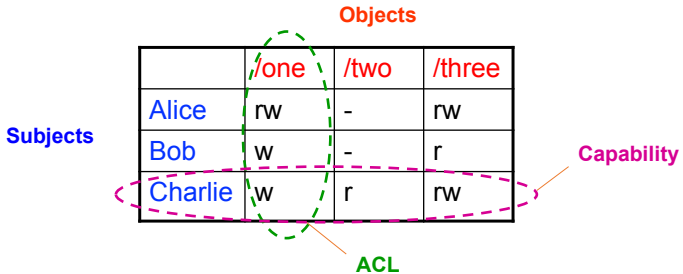
Representing Protection

Access Control Lists (ACL)

For each object, maintain a list of subjects and their permitted actions

Capabilities

For each subject, maintain a list of objects and their permitted actions



ACLs and Capabilities

Approaches differ only in how the table is represented

Capabilities are easier to transfer

- They are like keys, can handoff, does not depend on subject

In practice, ACLs are easier to manage

- Object-centric, easy to grant, revoke
- To revoke capabilities, have to keep track of all subjects that have the capability – a challenging problem

ACLs have a problem when objects are heavily shared

- The ACLs become very large
- Use groups (e.g., Unix)

Unix File Protection

What approach does Unix use in the FS?

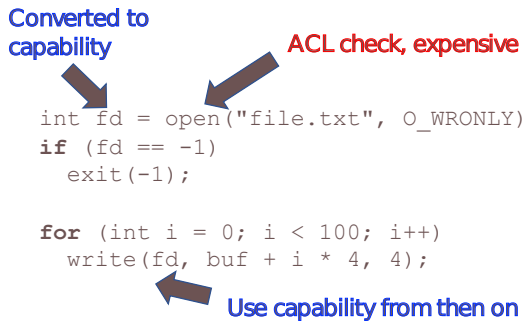
- Answer: both

ACL: Unix file permissions

Capability: file descriptors

How are they used together?

- Conversion through `open()` system call



Summary

Files

- Operations, access methods

Directories

- Operations, using directories to do path searches

Sharing

Protection

- ACLs vs. capabilities

Next Time

File Systems Implementation