Virtual File System

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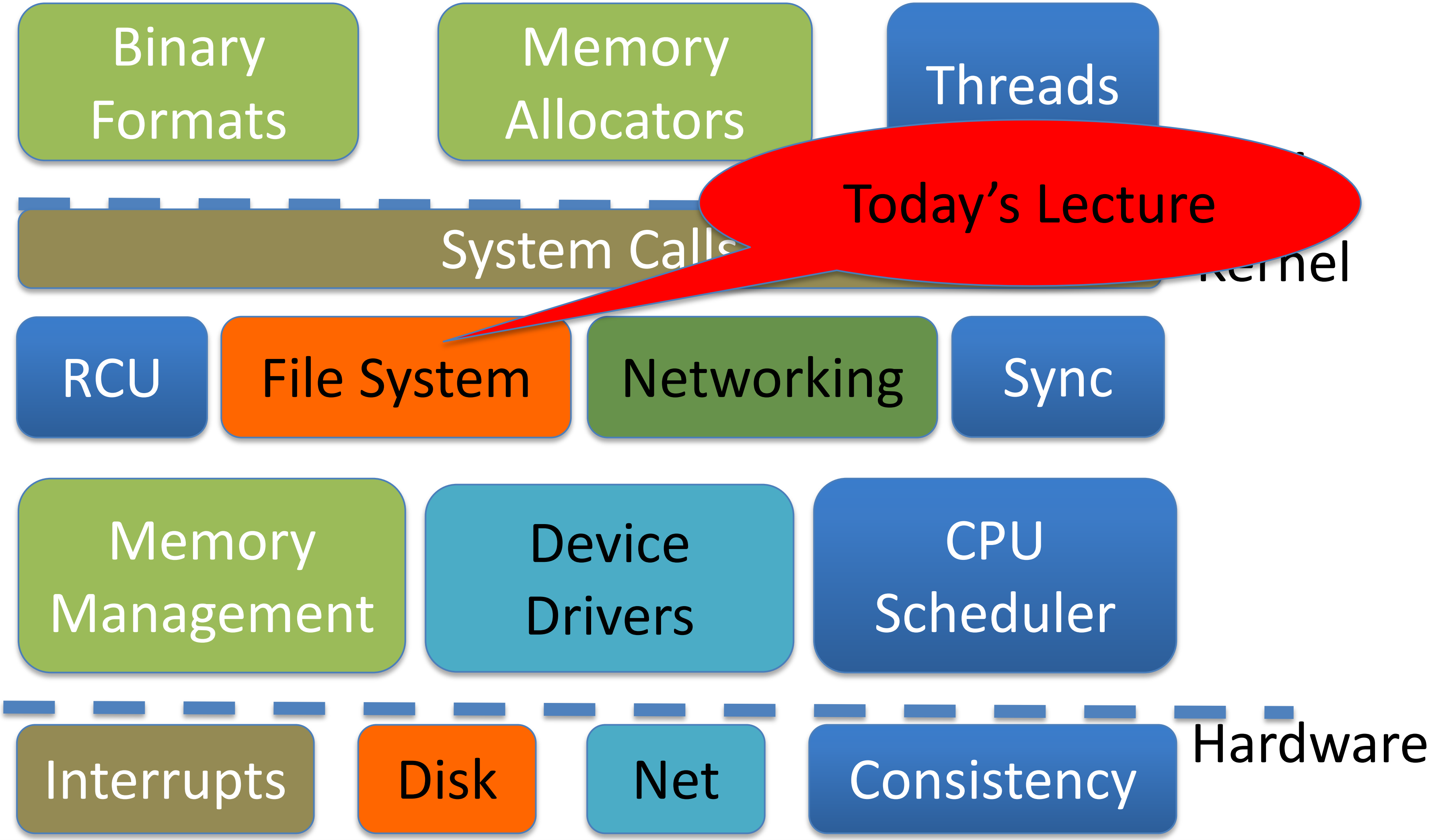
Logical Diagram



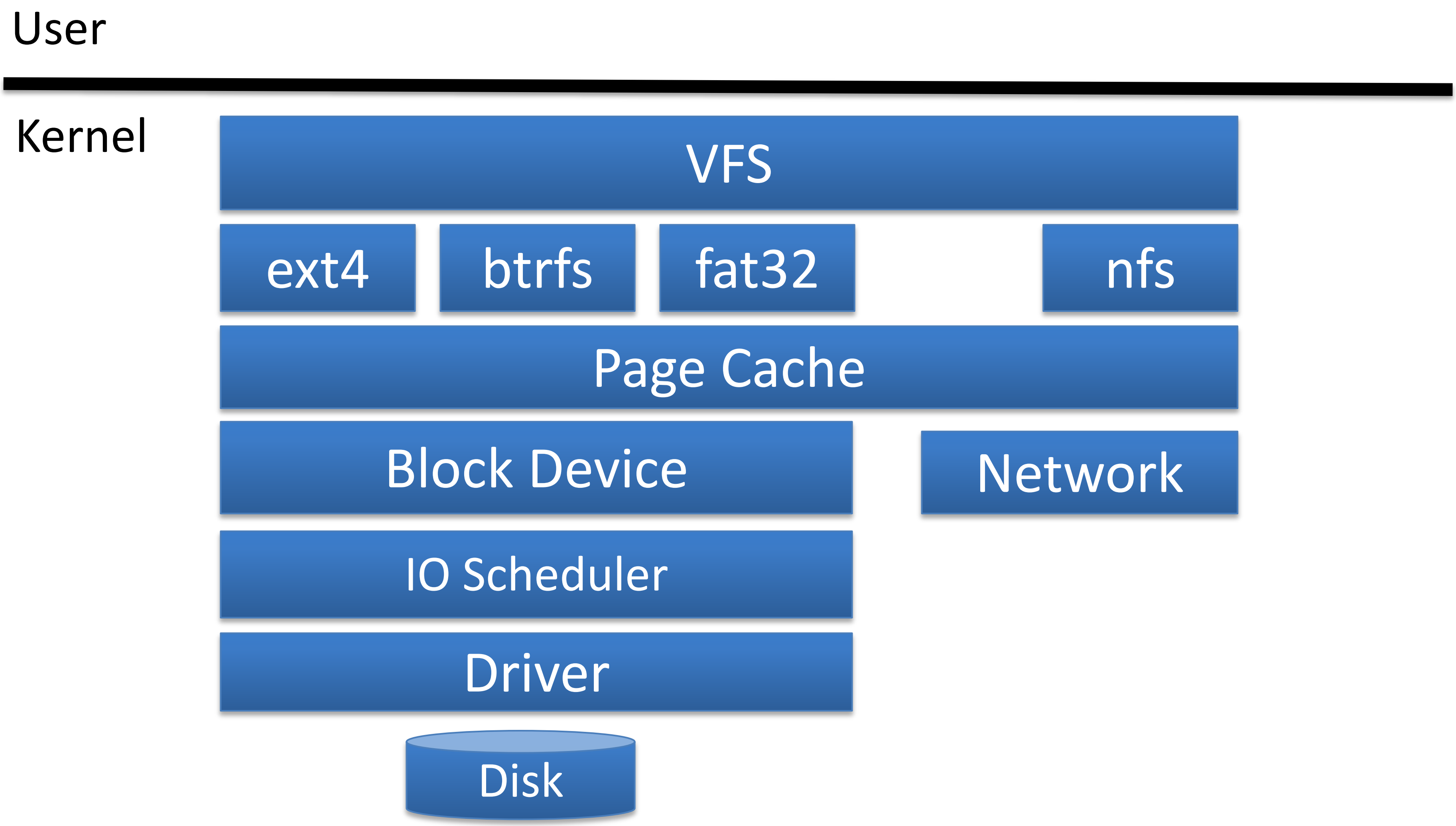
History

- Early OSes provided a single file system
  - In general, system was pretty tailored to target hardware
- In the early 80s, people became interested in supporting more than one file system type on a single system
  - Any guesses why?
  - Networked file systems – sharing parts of a file system transparently across a network of workstations

Modern VFS

- Dozens of supported file systems
  - Allows experimentation with new features and designs transparent to applications
  - Interoperability with removable media and other OSes
- Independent layer from backing storage
  - Pseudo FSes used for configuration (/proc, /devtmps…) only backed by kernel data structures
- And, of course, networked file system support

More detailed diagram



User

Kernel

VFS

ext4 btrfs fat32 nfs

Page Cache

Block Device

Network

IO Scheduler

Driver

Disk

User’s perspective

- Single programming interface
  - (POSIX file system calls – open, read, write, etc.)
- Single file system tree
  - A remote file system with home directories can be transparently mounted at /home
- Alternative: Custom library for each file system
  - Much more trouble for the programmer

What the VFS does

- The VFS is a substantial piece of code, not just an API wrapper
- Caches file system metadata (e.g., file names, attributes)
  - Coordinates data caching with the page cache
- Enforces a common access control model
- Implements complex, common routines, such as path lookup, file opening, and file handle management

FS Developer’s Perspective

- FS developer responsible for implementing a set of standard objects/functions, which are called by the VFS
  - Primarily populating in-memory objects from stable storage, and writing them back
- Can use block device interfaces to schedule disk I/O
  - And page cache functions
  - And some VFS helpers
- Analogous to implementing Java abstract classes

High-level FS dev. tasks

- Translate between volatile VFS objects and backing storage (whether device, remote system, or other/none)
  - Potentially includes requesting I/O
- Read and write file pages

Opportunities

- VFS doesn’t prescribe all aspects of FS design
  - More of a lowest common denominator
- Opportunities: (to name a few)
  - More optimal media usage/scheduling
  - Varying on-disk consistency guarantees
  - Features (e.g., encryption, virus scanning, snapshotting)

Core VFS abstractions

- super block – FS-global data
  - Early/many file systems put this as first block of partition
- inode (index node) – metadata for one file
- dentry (directory entry) – file name to inode mapping
- file – a file handle – refers to a dentry and a cursor in the file (offset)

Super blocks

- SB + inodes are *extended* by FS developer
- Stores all FS-global data
  - Opaque pointer (s_fs_info) for fs-specific data
- Includes many hooks for tasks such as creating or destroying inodes
- Dirty flag for when it needs to be synced with disk
- Kernel keeps a circular list of all of these

Inode

- The second object extended by the FS
  - Huge – more fields than we can talk about
- Tracks:
  - File attributes: permissions, size, modification time, etc.
  - File contents:
    - Address space for contents cached in memory
    - Low-level file system stores block locations on disk
  - Flags, including dirty inode and dirty data

Inode history

- Name goes back to file systems that stored file metadata at fixed intervals on the disk
  - If you knew the file’s index number, you could find its metadata on disk
- Hence, the name ‘index node’
- Original VFS design called them ‘vnode’ for virtual node (perhaps more appropriately)
- Linux uses the name inode

Embedded inodes

- Many file systems embed the VFS inode in a larger, FS-specific inode, e.g.,:

```
struct donfs_inode {
        int ondisk_blocks[];
        /* other stuff*/
        struct inode vfs_inode;
}
```

- Why? Finding the low-level data associated with an inode just requires simple (compiler-generated) math

Linking

- An inode uniquely identifies a file for its lifespan
  - Does not change when renamed
- Model: Inode tracks “links” or references on disk
  - Created by file names in a directory that point to the inode
  - Ex: renaming the file temporarily increases link count and then lowers it again
- When link count is zero, inode (and contents) deleted
  - There is no ‘delete’ system call, only ‘unlink’

Linking, cont.

- “Hard” link (link system call/ln utility): creates a second name for the same file; modifications to either name changes **contents**.
  - This is not a copy
- Open files create an in-memory reference to a file
  - If an open file is unlinked, the directory entry is deleted immediately, but the inode and data are retained until all in-memory references are deleted
- Common trick for temporary files:
  - create (1 link)
  - open (1 link, 1 ref)
  - unlink (0 link)
  - File gets cleaned up when program dies
    - (kernel removes last reference on exit)

Inode ‘stats’

- The ‘stat’ word encodes both permissions and type
- High bits encode the type: regular file, directory, pipe, char device, socket, block device, etc.
    - Unix: Everything’s a file! VFS involved even with sockets!
- Lower bits encode permissions:
    - 3 bits for each of User, Group, Other + 3 special bits
    - Bits: 2 = read, 1 = write, 0 = execute
    - Ex: 750 – User RWX, Group RX, Other nothing

Special bits

- For directories, ‘Execute’ means search
  - X-only permissions means I can find readable subdirectories or files, but can’t enumerate the contents
  - Useful for sharing files in your home directory, without sharing your home directory contents
    - Lots of information in meta-data!
- Setuid bit
  - Mostly relevant for executables: Allows anyone who runs this program to execute with owner’s uid
  - Crude form of permission delegation

More special bits

- Group inheritance bit
  - In general, when I create a file, it is owned by my default group
  - If I create in a ‘g+s’ directory, the directory group owns the file
  - Useful for things like shared git repositories
- Sticky bit
  - Restricts deletion of files

File objects

- Represent an open file; point to a dentry and cursor
  - Each process has a table of pointers to them
  - The int fd returned by open is an offset into this table
- These are VFS-only abstractions; the FS doesn't need to track which process has a reference to a file
- Files have a reference count. Why?
  - Fork also copies the file handles
  - If your child reads from the handle, it advances your (shared) cursor

File handle games

- dup, dup2 – Copy a file handle
  - Just creates 2 table entries for same file struct, increments the reference count
- seek – adjust the cursor position
  - Obviously a throw-back to when files were on tapes
- fcntl – Like ioctl (misc operations), but for files
- CLOSE_ON_EXEC – a bit that prevents file inheritance if a new binary is exec'ed (set by open or fcntl)

Dentries

- These store:
  - A file name
  - A pointer to an inode
  - A parent pointer (null for root of file system)
- Ex: /home/porter/vfs.pptx would have 4 dentries:
  - /, home, porter, & vfs.pptx
  - Parent pointer distinguishes /home/porter from /tmp/porter
- These are also VFS-only abstractions
  - Although inode hooks on directories can populate them

Why dentries?

- A simple directory model might just treat it as a file listing <name, inode> tuples
- Why not just use the page cache for this?
    - FS directory tree traversal very common; optimize with special data structures
- The dentry cache is a complex data structure we will discuss in much more detail later

Summary of abstractions

- Super blocks – FS- global data
- Inodes – stores a given file
- File (handle) – Essentially a <dentry, offset> tuple
- Dentry – Essentially a <name, parent dentry, inode> tuple

More on the user’s perspective

- Let’s wrap today by discussing some common FS system calls in more detail
- Let’s play it as a trivia game
    - What call would you use to…

Create a file?

- creat
- More commonly, open with the O_CREAT flag
  - Avoid race conditions between creation and open
- What does O_EXCL do?
  - Fails if the file already exists

Create a directory?

- mkdir
- But I thought everything in Unix was a file!?!
  - This means that *sometimes* you can read/write an existing handle, even if you don't know what is behind it.
  - Even this doesn't work for directories

Remove a directory

- rmdir

Remove a file

- unlink

Read a file?

- read()
- How do you change cursor position?
  - lseek (or pread)

Read a directory?

- readdir or getdents

Shorten a file

- truncate/ftruncate
- Can also be used to create a file full of zeros of abritrary length
  - Often blocks on disk are demand-allocated (laziness rules!)

What is a symbolic link?

- A special file type that stores the name of another file
- How different from a hard link?
  - Doesn't raise the link count of the file
  - Can be "broken," or point to a missing file
- How created?
  - symlink system call or 'ln –s' command

Let’s step it up a bit

How does an editor save a file?

- Hint: we don’t want the program to crash with a half-written file
- Create a backup (using open)
- Write the full backup (using read old/ write new)
- Close both
- Do a rename(old, new) to atomically replace

How does ‘ls’ work?

- dh = open(dir)
- for each file (while readdir(dh))
  - Print file name
- close(dh)

What about that cool colored text?

- dh = open(dir)
- for each file (while readdir(dh))
  - stat(file, &stat_buf)
  - if (stat & execute bit) color == green
  - else if …
  - Print file name
  - Reset color
- close(dh)

Summary

- Today’s goal: VFS overview from many perspectives
  - User (application programmer)
  - FS implementer
    - Used many page cache and disk I/O tools we’ve seen
- Key VFS objects
- Important to be able to pick POSIX fs system calls from a line up
  - Homework: think about pseudocode from any simple command-line file system utilities you type this weekend