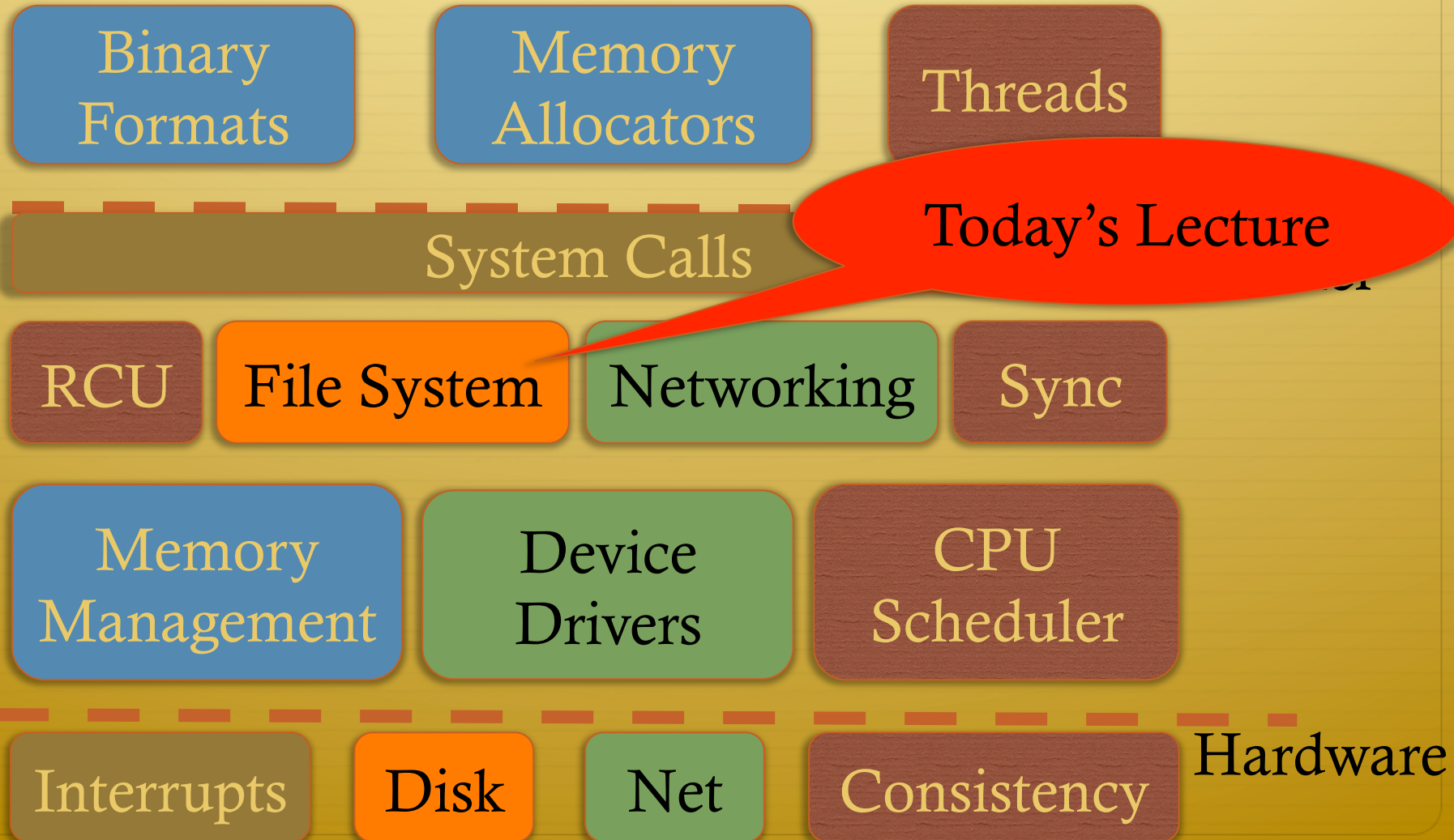


Logical Diagram



History



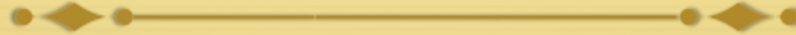
- ✦ Early OSes provided a single file system
 - ✦ In general, system was pretty tailored to target hardware
- ✦ In the early 80s, people became interested in supporting more than one file system type on a single system
 - ✦ Any guesses why?
 - ✦ Networked file systems – sharing parts of a file system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

Modern VFS



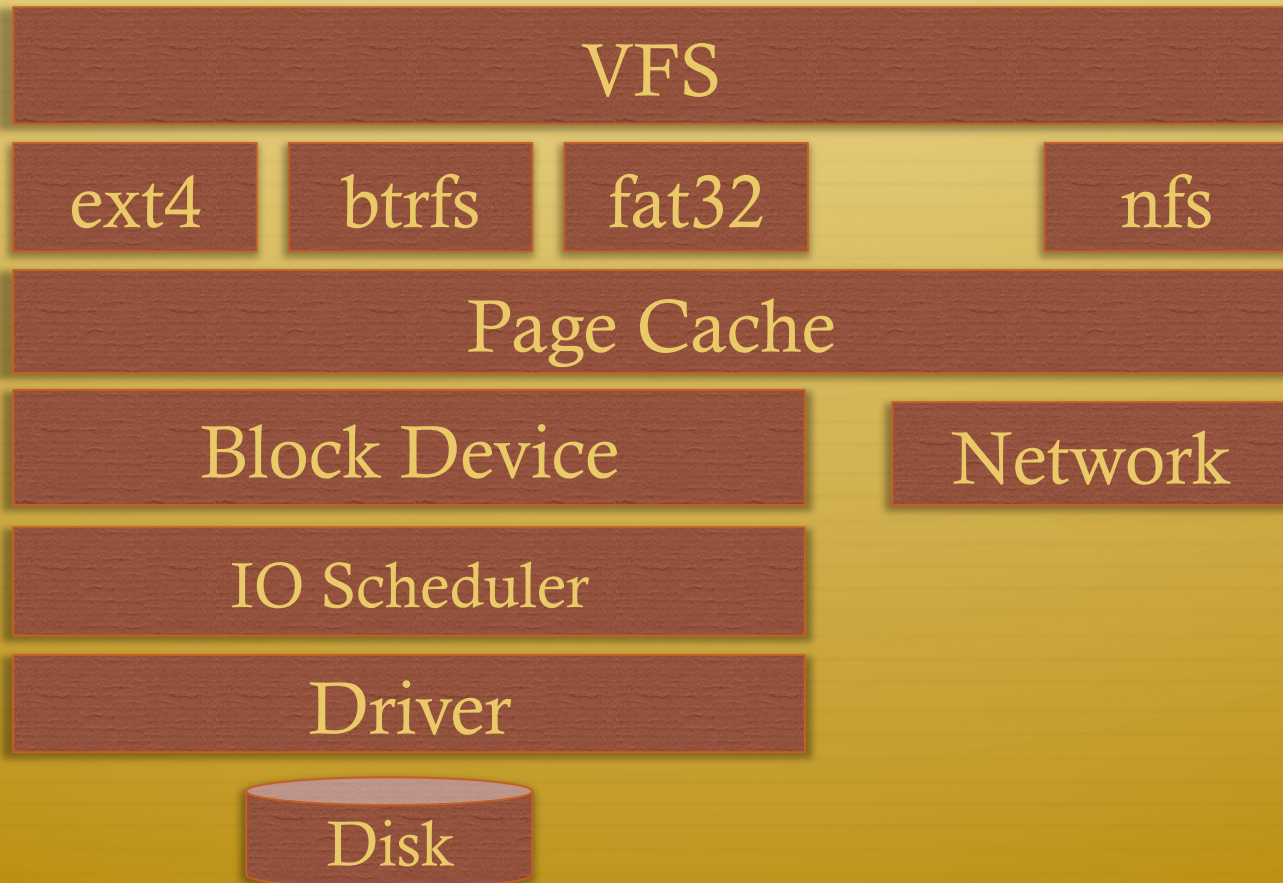
- ✦ Dozens of supported file systems
 - ✦ Allows experimentation with new features and designs transparent to applications
 - ✦ Interoperability with removable media and other OSES
- ✦ Independent layer from backing storage
 - ✦ Pseudo FSes used for configuration (/proc, /devtmps...) only backed by kernel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

More detailed diagram



User

Kernel



User's perspective



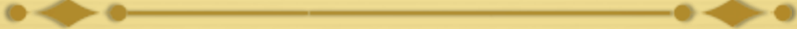
- ✦ Single programming interface
 - ✦ (POSIX file system calls – open, read, write, etc.)
- ✦ Single file system tree
 - ✦ A remote file system with home directories can be transparently mounted at /home
- ✦ Alternative: Custom library for each file system
 - ✦ Much more trouble for the programmer

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 link 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 $\langle \text{name, inode} \rangle$ 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 \langle dentry, offset \rangle tuple
- ✦ Dentry – Essentially a \langle name, parent dentry, inode \rangle 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?



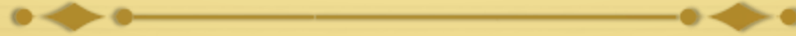
- ✦ mkdir
- ✦ But I thought everything in Unix was a file!?!
 - ✦ This means that *sometimes* you can read/write an existing handle, even if you don't know what is behind it.
 - ✦ Even this doesn't work for directories

Remove a directory



✦ `rmdir`

Remove a file



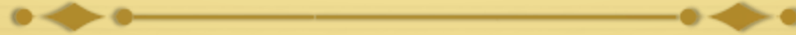
✦ unlink

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 arbitrary 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 = opendir(dir)`
- ✦ for each file (`while readdir(dh)`)
 - ✦ `stat(file, &stat_buf)`
 - ✦ if `(stat & execute bit) color == green`
 - ✦ else if ...
 - ✦ Print file name
 - ✦ Reset color
- ✦ `closedir(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