CSE 506: Operating Systems

Virtual File System

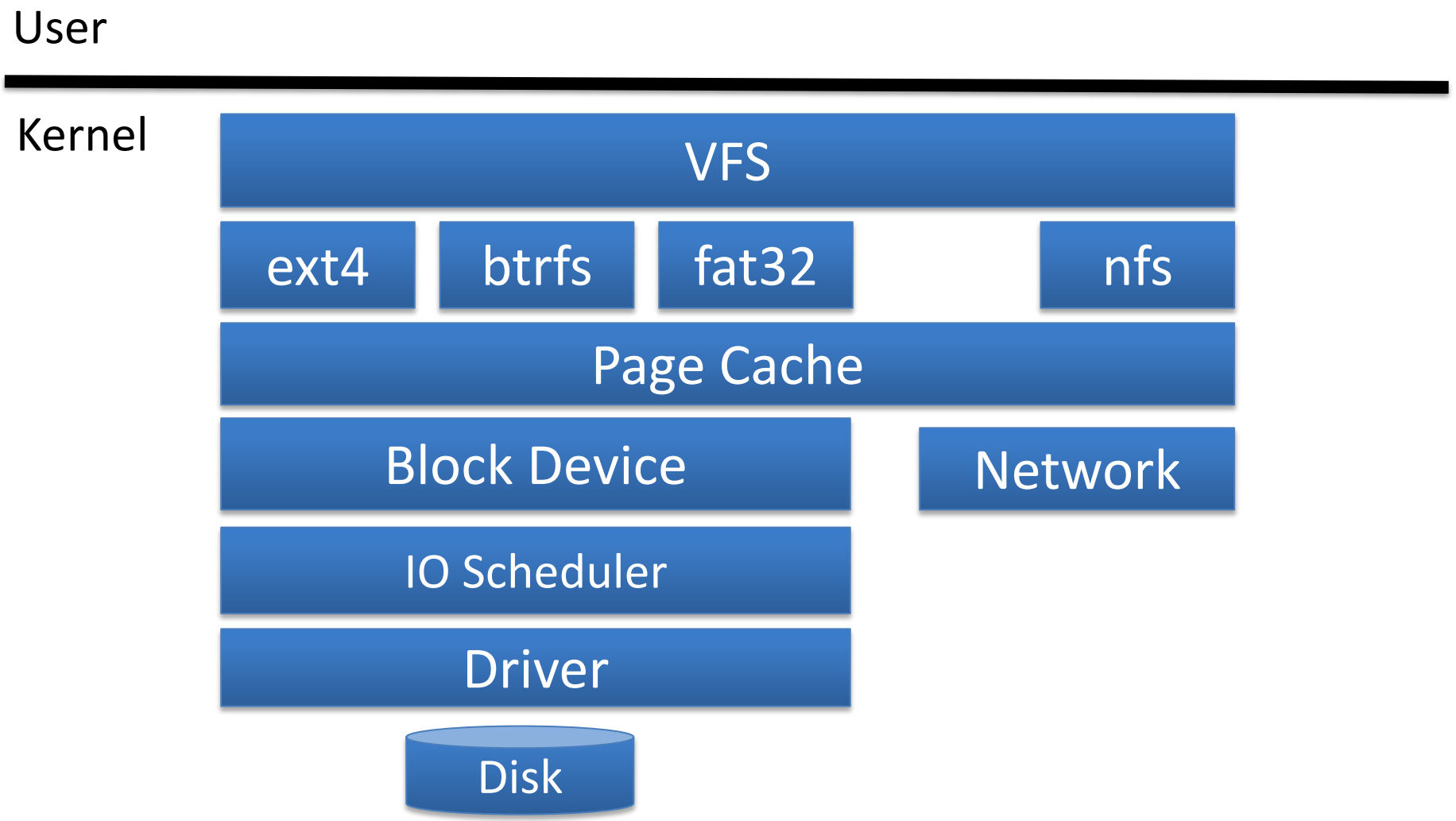
History

- Early OSes provided a single file system
  - In general, system was tailored to target hardware
- In the early 80s, desire for more than one file system
  - Any guesses why?
  - Networked file systems
    - Sharing parts of a file system across a network of workstations

Modern VFS

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

More detailed diagram



User's perspective

- Single programming interface
  - (POSIX file system calls – open, read, write, etc.)
- Single file system tree
  - Remote FS can be transparently mounted (e.g., 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., names, attributes)
  - Coordinates data caching with the page cache
- Enforces a common access control model
- Implements complex, common routines
  - path lookup
  - opening files
  - file handle management

FS Developer's Perspective

- FS developer responsible for…
  - Implementing standard objects/functions called by the VFS
    - Primarily populating in-memory objects
      - Typically from stable storage
    - Sometimes 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 VFS objects and backing storage (whether device, remote system, or other/none)
  - Potentially includes requesting I/O
- Read and write file pages
- VFS doesn't prescribe all aspects of FS design
  - More of a lowest common denominator

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) –name to inode mapping
- file – ***file descriptor*** – dentry and cursor (file offset)

Super blocks

- SB + inodes are extended by file system developer
- Stores all FS-global data
  - Opaque pointer (s_fs_info) for FS-specific data
- Includes many hooks
  - 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
  - When there are multiple FSes (in today's systems: always)

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

- Original file systems stored files at fixed intervals
  - If you knew the file's index number
    - you could find its metadata on disk
  - Thing of a portion of the disk as a big array of metadata
- Hence, the name 'index node'
- Original VFS design called them 'vnode'
  - virtual node (perhaps more appropriately)
  - Linux uses the name inode

Embedded inodes

- Many FSes embed VFS inode in FS-specific inode

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

- Why?
  - Finding the low-level from inode is simple
    - Compiler translates references to simple math

Linking

- An inode uniquely identifies a file for its lifespan
  - Does not change when renamed
- Model: inode tracks "links" or references on disk
  - Count "1" for every reference on disk
  - Created by file names in a directory that point to the inode
    - What happens when a file is renamed?
      - renaming file temporarily increases link count and then lowers it (at least in some implementations)
- 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 new name for the same inode
    - Opening either name opens the *same* file
  - 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
    - inode and data retained until all in-memory references are deleted
  - Famous feature: `rm` on large open file when out of quota
    - Still out of quota

Common trick for temporary files

- How to clean up temp file when program crashes?
  - create (1 link)
  - open (1 link, 1 ref)
  - unlink (0 link)
  - File gets cleaned up when program dies
    - Kernel removes last reference on exit
    - Happens regardless if exit is clean or not
    - Except if the kernel crashes / power is lost
      - Need something like fsck to "clean up" inodes without dentries
        - » Dropped into `lost+found` directory

inode 'stats'

- The 'stat' word encodes both permissions and type
- High bits encode the type:
  - regular file, directory, pipe, device, socket, 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
    - How about the "sticky" bit? "suid" bit?
  - `chmod` has more pleasant syntax [ugs][+-][rwx]

Special bits

- For directories, ‘Execute’ means search
  - X-only allows to find readable subdirectories or files
    - Can’t enumerate the contents
    - Useful for sharing files in your home directory
      - Without sharing your home directory contents
- Setuid bit
  - Program executes with owner’s UID
  - Crude form of permission delegation

More special bits

- Group inheritance bit
  - When I create a file, it is owned by my default group
  - When I create in a ‘g+s’ directory, directory group owns file
    - Useful for things like shared git repositories
- Sticky bit
  - Prevents non-owners from deleting or renaming files
    - Ex: CSE506 submission directory

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
- VFS-only abstractions
  - FS doesn't track which process has a reference to a file
- Files have a reference count. Why?
  - Fork also copies the file handles
    - Particularly important for stdin, stdout, stderr
  - If child reads from the handle, it advances (shared) cursor
    - These days, hard to tell if this is a "feature" or a "bug"

File handle games

- `dup()`, `dup2()` – Copy a file handle
  - Creates 2 table entries for same file struct
    - Increments the reference count
- `seek()` – adjust the cursor position
  - Back when files were on tape…
- `fcntl()` – Set flags on file (`ioctl()` for inodes)
  - `CLOSE_ON_EXEC` – bit prevents inheritance on `exec()`
    - Set by `open()` or `fcntl()`

Dentries

- These store:
  - A file name
  - A link to an inode
  - A parent ptr (null for root of file system)
- Ex: /home/myuser/vfs.pptx may have 4 dentries:
  - /, home, myuser, and vfs.pptx
  - Parent ptr distinguishes /home/myuser from /tmp/myuser
- Also VFS-only abstraction
  - Although inode hooks on directories can populate them

Why dentries?

- Simple directory model can treat it as a file
  - Contents are a list of <name, inode> tuples
- Why not just use the page cache?
  - FS directory tree traversal very common
    - Optimize with special data structures
    - No need to re-parse and traverse on-disk layout format
- The dentry cache is a complex data structure
  - We will discuss in more detail later

Symbolic Links

- Special file type that stores a string
  - String usually assumed to be a filename
  - Created with `symlink()` system call
- How different from a hard link
  - Completely
  - Doesn't raise the link count of the file
  - Can be "broken," or point to a missing file (just a string)
- Sometimes abused to store short strings

```
[myself@newcastle ~/tmp]% ln -s "silly example" mydata
[myself@newcastle ~/tmp]% ls -l
lrwxrwxrwx 1 myself mygroup 23 Oct 24 02:42 mydata -> silly example
```

How does a text editor save a file?

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

What does /bin/ls do?

- dh = opendir(dir)
- foreach file (while readdir(dh))
  - stat(file, &stat_buf)
  - if (stat & execute bit) color == green
  - else if …
  - Print file name
  - Reset color
- closedir(dh)

Quick review: dentry

- What purpose does a dentry serve?
  - Maps a path name to an inode
    - More in 2 slides on how to find a dentry
- dentries are cached in memory
  - Only “recently” accessed parts of dir are in memory
    - Others may need to be read from disk
  - dentries can be freed to reclaim memory (like pages)

dentry Caching

- 3 cases for a dentry:
  - In memory (exists)
  - Not in memory (doesn't exist)
  - Not in memory (on disk/evicted for space or never used)
- How to distinguish last 2 cases?
  - Case 2 can generate a lot of needless disk traffic
  - "Negative" dentry – Dentry with a NULL inode pointer

dentry Tracking

- dentries are stored in four data structures:
  - A hash table (for quick lookup)
  - A LRU list (for freeing cache space wisely)
  - A child list of subdirectories (mainly for freeing)
  - An alias list (to do reverse mapping of inode -> dentries)
    - Recall that many names can point to one inode

Summary of `open()` Implementation

- Key kernel tasks:
  - Map a human-readable path name to an inode
    - Check access permissions, from / to the file
  - Possibly create or truncate the file (O_CREAT, O_TRUNC)
  - Create a file struct
    - Allocate a descriptor
      - Point descriptor at file struct
  - Return descriptor

`open()` arguments

```
int open(char *path, int flags, int mode);
```

- Path: file name
- Flags: many (see manual page)
- Mode: If creating file, what perms? (e.g., 0755)
- Return value: File handle index (>= 0 on success)
  - Or (0 –errno) on failure

Absolute vs. Relative Paths

- Each process has root and working directories
  - Stored in pcb->root (or pcb->fs) and pcb->cwd
    - These are dentry pointers (not strings)
- Why store a current root directory?
  - Some programs are "`chroot` jailed"
    - Should not be able to access anything outside of the jail

More on paths

- An absolute path starts with the '/' character
  - E.g., /home/myself/foo.txt, /lib/libc.so
- A relative path starts with anything else:
  - E.g., vfs.pptx, ../../etc/apache2.conf
- First character dictates where to start searching
  - Only two options: root (absolute) or cwd (relative)

Search

- Execute in a loop looking for next piece
  - Treat '/' character as component delimiter
  - Each iteration looks up part of the path
- Ex: '/home/myself/foo' would look up…
  - 'home', 'myself', then 'foo', starting at '/'

Iteration 1

- For searched dentry (/), dereference the inode
- Check access permission (mode is stored in inode)
  - Use `permission()` function pointer on inode
    - Can be overridden by a file system
- If ok, look at next path component (/home)

Detail (2)

- Some special cases:
  - If next component is a '.', just skip it
  - If next component is a '..', move up to parent
    - Catch special case where current dentry is root
      - Treat this as a no-op
- If not a '.' or '..':
  - Compute a hash value to find bucket in `d_hash` table
  - Hash of path from root (e.g., '/home/foo', not 'foo')
  - Search the `d_hash` bucket at this hash value

Detail (3)

- If no dentry in the hash bucket
  - Call `lookup()` method on parent inode (provided by FS)
    - Probably will read the dentry from disk
      - Or the network, or kernel data structures, …
- If dentry found, check if it is a symlink
  - If so, call inode->readlink() (also provided by FS)
    - Get the path stored in the symlink
  - Then continue next iteration
    - First char decides to start at root or at cwd again
- If not a symlink, check if it is a directory
  - If not a directory and not last element, we have a bad path

Iteration 2

- We have dentry/inode for /home, now finding myself
- Check permission in /home
- Hash /home/myself, find dentry
- Confirm not ‘.’, ‘..’, or a symlink
- Confirm is a directory
- Repeat with dentry/inode for /home/myself
  - Search for foo

Symlink Loops

- What if /home/myself/foo is a symlink to 'foo'?
  - Kernel gets in an infinite loop
- Can be more subtle:
  - foo -> bar
  - bar -> baz
  - baz -> foo

Preventing infinite symlink recursion

- More heuristics
- If more than 40 symlinks resolved
  - quit with –ELOOP
- If more than 6 symlinks in a row without non-symlink
  - quit with –ELOOP
- Can prevent execution of legitimate 41 symlink path
  - Better than an infinite loop

Back to `open()`

- Key tasks:
  - Map a human-readable path name to an inode
    - Check access permissions, from / to the file
  - Possibly create or truncate the file (O_CREAT, O_TRUNC)
  - Create a file descriptor
- We've seen how first few steps are done

Creation

- Handled as part of search; last item is special
  - Usually, if an item isn't found, search returns an error
- If last item (foo) exists and `O_EXCL` flag set, fail
  - If `O_EXCL` is not set, return existing dentry
- If it does not exist, call FS create method
  - Make a new inode and dentry
    - Then open it
- Why is Create a part of Open?
  - Avoid races in "if (!exist()) create(); open();"

File descriptors

- Descriptors index into per-process array of struct file
- struct file stores
  - dentry pointer
  - cursor into the file
  - permissions (cache of inode's value)
  - reference count
- `open()` marks a free table entry as 'in use'
  - If full, create a new table 2x the size and copies old one
  - Allocate a new file struct and put a pointer in table

Once `open()`, can `read()`

```
int read(int fd, void *buf, size_t bytes);
```

- fd: File descriptor index
- buf: Buffer kernel writes the read data into
- bytes: Number of bytes requested
- Returns: bytes read (if >= 0), or –errno

Summary of `read()` Implementation

- Translate `int fd` to a struct file (if valid)
  - Check cached permissions in the file
  - Increase reference count
    - FS `read()` routine might context switch away temporarily
- Do `read()` routine associated with file (FS-specific)
  - Probe the page cache for data
  - Access storage if needed
    - Can even do both: read() is allowed to return less than requested
- Drop refcount, return bytes read

Copying data to user

- Kernel needs to be sure that buffer is a valid address
  - Validate that `buf` is a valid address
    - And that `buf` size>=`bytes` requested
- How to do it?
  - Can walk appropriate page table entries
- What could go wrong?
  - Concurrent munmap from another thread
  - Page might be lazy allocated by kernel

Trick for Validating User Buffers

- What if we don't do all of this validation?
  - Looks like kernel had a page fault
  - Usually *really bad*
- Idea: set kernel flag in_copy_to_user
  - If a page fault happens for a user address, don't panic
    - Just handle demand faults
  - If the page is really bad
    - Set indicator that write loop should be aborted
      - Indicator can be left in a register
        - » Tricky context switch code while exiting the page fault

Zero-Copy

- How many memory copies needed for a large read?
  - One in page cache
  - One in user space
- What if we then write this to network?
  - One more for NIC driver
- Avoided extra copies if read/write is page-granularity
  - Steal physical page containing buffer from process
  - Replace it with physical page from page cache
    - Mark it as COW in process, just in case
  - Avoids unnecessary copies in common case