VFS, Continued

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Previous lectures

- Basic VFS abstractions
  - Including data structures
  - And programming model (file system)
  - And APIs
- Some system call examples
- Walk through some system calls
- Plus synchronization issues

Today's goal: Synthesis

- Walk through two system calls in some detail
  - Open and read
- Too much code to cover all FS system calls

Quick review: dentry

- What purpose does a dentry serve?
  - Essentially 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 a directory 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 directories can map one inode

Open summary

- 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 descriptor

Open arguments

- int open(const char *path, int flags, int mode);
- Path: file name
- Flags: many (see manual page), include read/write perms
- Mode: If a file is created, what permissions should it have? (e.g., 0755)
- Return value: File handle index (>= 0 on success)
  - Or (0 –errno) on failure

Absolute vs. Relative Paths

- Each process has a current root and working directory
  - Stored in current->fs-> (fs, pwd---respectively)
  - Specifically, these are dentry pointers (not strings)
  - Note that these are shared by threads
- Why have a current root directory?
  - Some programs are 'chroot jailed' and should not be able to access anything outside of the directory

More on paths

- An absolute path starts with the '/' character
  - E.g., /home/porter/foo.txt, /lib/libc.so
- A relative path starts with anything else:
  - E.g., vfs.pptx, ../../etc/apache2.conf
- First character dictates where in the dcache to start searching for a path

Search

- Executes in a loop, starting with the root directory or the current working directory
- Treats '/' character in the path as a component delimiter
- Each iteration looks up part of the path
- E.g., '/home/porter/foo' would look up 'home', 'porter', then 'foo', starting at /

Detail (iteration 1)

- For current dentry (/), dereference the inode
- Check access permission (recall, mode is stored in inode)
  - Use a permission() function pointer associated with the inode – can be overridden by a security module (such as SeLinux, or AppArmor), or the file system
- If ok, look at next path component (/home)

Detail (2)

- Some special cases:
  - If next component is a ‘.’, just skip to next component
  - If next component is a ‘..’, try to move up to parent
    - Catch the special case where the current dentry is the process root directory and treat this as a no-op
- If not a ‘.’ or ‘..’:
  - Compute a hash value to find bucket in d_hash table
  - Hash is based on full path (e.g., /home/foo, not ‘foo’)
  - Search the d_hash bucket at this hash value

Detail (3)

- If there isn't a dentry in the hash bucket, calls the lookup() method on parent inode (provided by FS), to read the dentry from disk
  - Or the network, or kernel data structures…
- If found, check whether it is a symbolic link
  - If so, call inode->readlink() (also provided by FS) to get the path stored in the symlink
  - Then continue next iteration
- 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 porter
- Check permission in /home
- Hash /home/porter, find dentry
- Confirm not '.', '..', or a symlink
- Confirm is a directory
- Recur with dentry/inode for /home/porter, search for foo

Symlink problems

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

Preventing infinite recursion

- More simple heuristics
- If more than 40 symlinks resolved, quit with –ELOOP
- If more than 6 symlinks resolved in a row without a non-symlink inode, quit with –ELOOP
  - Maybe add some special logic for obvious self-references
- Can prevent execution of a legitimate 41 symlink path
  - Generally considered reasonable

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 steps 1 and 2 are done

Creation

- Handled as part of search; treat last item specially
  - 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 to make a new inode and dentry
  - This is then returned

File descriptors

- User-level file descriptors are an index into a process-local table of struct files
- A struct file stores a dentry pointer, an offset into the file, and caches the access mode (read/write/both)
  - The table also tracks which entries are valid
- Open marks a free table entry as 'in use'
  - If full, create a new table 2x the size and copy old one
  - Allocates a new file struct and puts a pointer in table

Truncation

- The O_TRUNC flag causes the file to be truncated to zero bytes at the end of opening
- This is done with a routine that frees cached pages, updates inode size, and calls an FS-provided truncate() hook
  - This routine generally updates on-disk data, freeing stored blocks

Open questions?

Now on to 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

Simple steps

- Translate int fd to a struct file (if valid)
  - Check cached permissions in the file
  - Increase reference count
- Validate that sizeof(buf) >= bytes requested
  - And that buf is a valid address
- Do read() routine associated with file (FS-specific)
- Drop refcount, return bytes read

Hard part: Getting data

- In addition to an offset, the file structure caches a pointer to the address space associated with the file
  - Recall: this includes the radix tree of in-memory pages
- Search the radix tree for the appropriate page of data
- If not found, or PG_uptodate flag not set, re-read from disk
- If found, copy into the user buffer (up to inode->i_size)

Requesting a page read

- First, the page must be locked
  - Atomically set a lock bit in the page descriptor
  - If this fails, the process sleeps until page is unlocked
- Once the page is locked, double-check that no one else has re-read from disk before locking the page
  - Also, check that no one has freed the page while we were waiting (by changing the mapping field)
- Invoke the address_space->readpage() method (set by FS)

Generic readpage

- Recall that most disk blocks are 512 bytes, yet pages are 4k
  - Block size stored in inode (blkbits)
- Each file system provides a get_block() routine that gives the logical block number on disk
- Check for edge cases (like a sparse file with missing blocks on disk)

More readpage

- If the blocks are contiguous on disk, read entire page as a batch
- If not, read each block one at a time
- These block requests are sent to the backing device I/O scheduler (recall lecture on I/O schedulers)

After readpage

- Mark the page accessed (for LRU reclaiming)
- Unlock the page
- Then copy the data, update file access time, advance file offset, etc.

Copying data to user

- Kernel needs to be sure that buffer is a valid address
- 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

- What if we don't do all of this validation?
  - Looks like kernel had a page fault
  - Usually REALLY BAD
- Idea: set a kernel flag that says we are 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, write an error code into a register so that it breaks the write loop; check after return

Benefits

- This trick actually speeds up the common case (buf is ok)
- Avoids complexity of handling weird race conditions
- Still need to be sure that buf address isn't in the kernel

Summary

- Goal: Synthesize key VFS concepts, data structures, and optimizations with concrete examples
- Understand key steps in open and read system calls