CSE 506: Operating Systems

File Systems

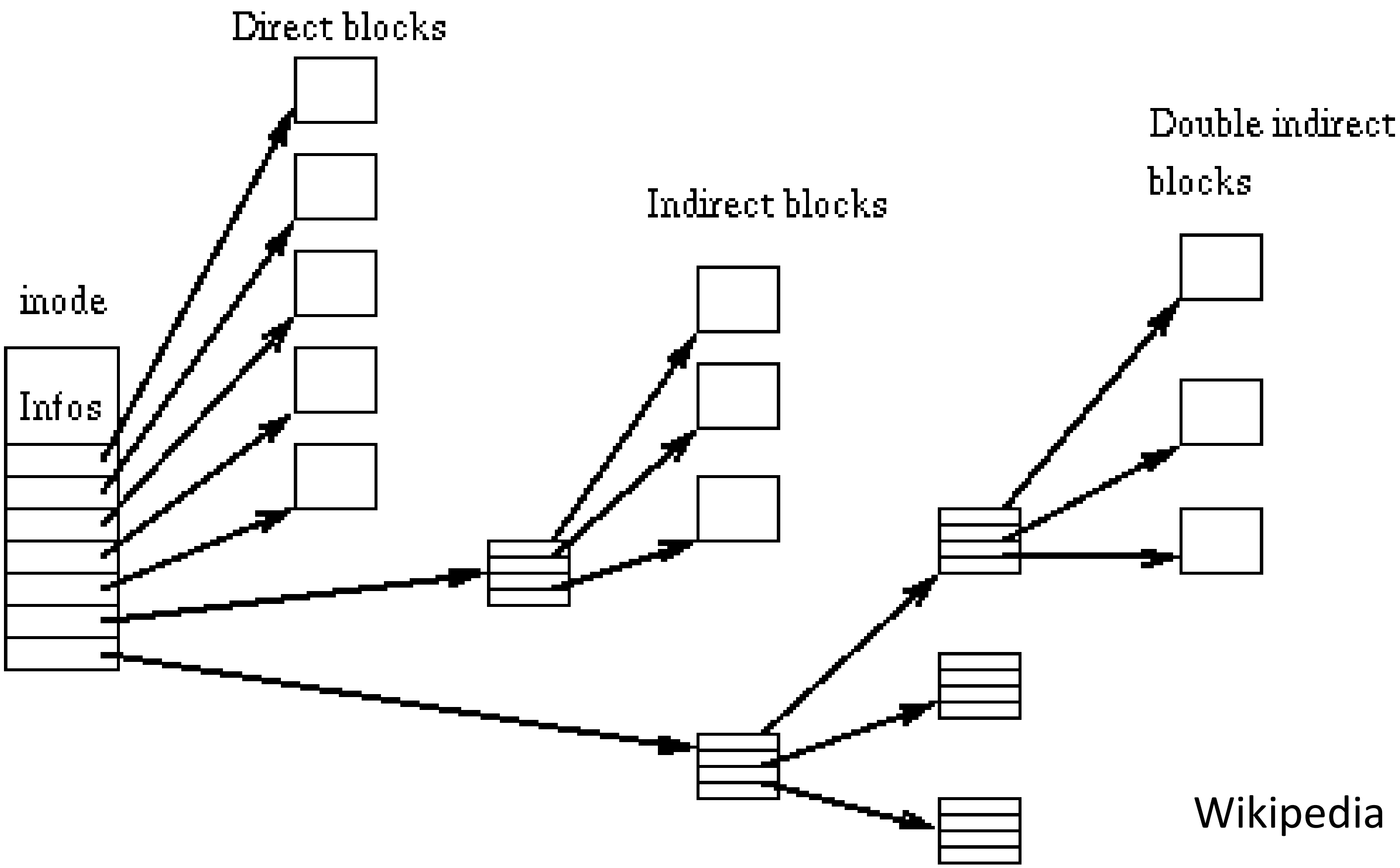
Traditional File Systems

- “FS”, UFS/FFS, Ext2, …
- Several simple on disk structures
  - Superblock
    - ***magic*** value to identify filesystem type
    - Places to find metadata on disk (e.g., inode array, free block list)
  - Inode array
    - Attributes (e.g., file or directory, size)
    - Pointers to data blocks
      - Several ***direct*** blocks for small files
      - ***{Singly, Doubly, Triply}-Indirect*** blocks for large files
  - Blocks
    - File contents

Working with a File System

- Need to ***format*** disk prior to use
  - Write a superblock
    - With correct magic number
  - Write details about disk size/number of blocks
    - Need a free list or bitmap
  - Write first several inodes
    - Usually “root” directory inode has designated index (e.g., “2”)
- Done with ***newfs***
  - Works on raw device (via /dev/diskdriver)
  - For course project, create program on host
    - Avoid the hassle of allowing formatting from inside your OS

Locating/Allocating Blocks



Wikipedia Ext2

Tracking Free Objects on Disk

- Use blocked pointed to from inode
  - On erase, must replace freed blocks onto free “list”
- Disk size traditionally known in advance
  - Disk maintains list of free blocks
    - Easy to keep track of in a bitmap
  - Virtual machine disks can be resized
    - Requires resizing filesystem to accept new blocks
      - Add elements to free list or mark bits in free map
- Need to maintain list of free inodes too
  - Otherwise must probe inode map for free slot
  - Superblock should remember head of list

File Systems and Crashes

- What can go wrong?
  - Write a block pointer in an inode
    … before marking block as used in bitmap
  - Write a reclaimed block into an inode
    … before removing old inode that points to it
  - Allocate an inode
    … without putting it in a directory
    - Inode is “orphaned”
  - Etc.

Deeper Issue

- Operations span multiple on-disk data structures
  - Requires more than one disk write
    - Multiple disk writes not performed together
      - Single sector writes aren't guaranteed either (e.g., power loss)
- Disk writes are always a series of updates
  - System crash can happen between any two updates
    - Crash between dependent updates leaves structures inconsistent!

Atomicity

- Property that something either happens or it doesn't
  - No partial results
- Desired for disk updates
  - Either inode bitmap, inode, *and* directory are updated
    - … or none of them are
- Preventing corruption is fundamentally hard
  - If the system is allowed to crash

fsck

- When file system mounted, mark on-disk superblock
  - If system is cleanly shut down, last disk write clears this bit
  - If the file system isn’t cleanly unmounted, run ***fsck***
- Does linear scan of all bookkeeping
  - Checks for (and fixes) inconsistencies
  - Puts orphaned pieces into /lost+found

fsck Examples

- Walk directory tree
  - Make sure each reachable inode is marked as allocated
- For each inode, check the reference count
  - Make sure all referenced blocks are marked as allocated
- Double-check that blocks and inodes are reachable
  - Or in free list
- Summary: very expensive, slow scan of file system

Journaling

- Idea: Keep a log of metadata operations
  - On system crash, look at data structures that were involved
- Limits the scope of recovery
  - Faster fsck
    - Cheap enough to be done while mounting

Two Ways to Journal (Log)

- Two main choices for a journaling scheme
  - (Borrowed/developed along with databases)
  - Often referred to as ***logging***
    - Called ***journaling*** for filesystems (usually metadata only)
- Undo: write how to go back to sane state
- Redo: write how to go forward to sane state

Undo Logging

1. Write what you are about to do (and how to undo)
2. Make changes on rest of disk
3. Write ***commit record*** to log
   – Marks logged operations as complete

- If system crashes before log commit record
  - Execute undo steps when recovering
- Undo steps *must* be on disk before other changes

Redo Logging

1. Write planned operations to the log
   – At the end, write a commit record
2. Make changes on rest of disk
3. When updates are done, mark log entry obsolete

- If system crashes during (2) or (3)
  – Re-execute all steps when recovering

Journaling Used in Practice

- Ext3 uses redo logging
- Easier to defer taking something apart
  … than to put it back together later
  - Delete something
  - Reuse a block for something else
    - Before journal entry commits
- Only works if data comfortably fits into memory
  - Databases often use undo logging
    - Avoid loading and writing large data sets twice

Atomicity Strategies

- Write journal log entry to disk
  - Include transaction number (sequence counter)
  - Write global counter to indicate log entry was written
    - This write is point at which journal is “committed”
      - Sometimes called a linearization point
    - Either the sequence number is written or not
      - Sequence number not written until log entry on disk
- Can also overwrite same spot at the end of log entry
  - First write entry with “incomplete” flag
  - Second entry with identical contents and “complete” flag

Batching of Journal writes

- Journaling would requires many synchronous writes
  - Synchronous writes are expensive
- Can batch multiple transactions into big one
  - Assuming no fsync()
  - Use a heuristic to decide on transaction size
    - Wait up to 5 seconds
    - Wait until disk block in the journal is full
- Batching reduces number of synchronous writes

ext4

- ext3 has some limitations
  - Ex: Can't work on large data sets
    - Can't fix without breaking backwards compatibility
- ext4 removes limitations
  - Plus adds a few features

Example

- Ext3 limited to 16 TB max size
  - 32-bit block numbers (2^{32} * 4k block size)
  - Can’t make bigger block sizes on disk
  - Can’t fix without breaking backwards compatibility
- Ext4 – 48 bit block numbers

Indirect Blocks vs. Extents

- Instead of representing each block
  - Represent contiguous chunks of blocks with an ***extent***
- More efficient for large files
  - Ex.: Disk blocks 50—300 represent blocks 0—250 of file
    - Vs.: Allocate and initialize 250 slots in an indirect block
    - Deletion requires marking 250 slots as free
- Worse for highly fragmented or sparse files
  - If no contiguous blocks, need extent for each block
  - Basically a more expensive indirect block scheme

Static Inode Allocations

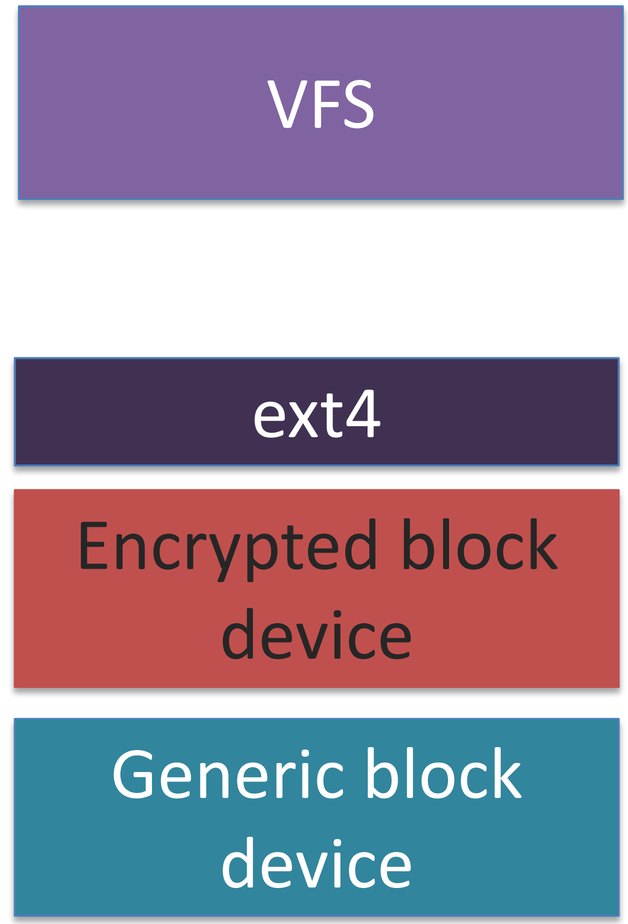
- When ext3 or ext4 file system created
  - Create all possible inodes
    - Can’t change count after creation
- If need many files, format for many inodes
  - Simplicity
    - Fixed inode locations allows easy lookup
    - Dynamic tracking requires another data structure
      - What if that structure gets corrupted?
    - Bookkeeping more complicated when blocks change type
  - Downsides
    - Wasted space if inode count is too high
    - Available capacity, but out of space if inode count is too low

Directory Scalability

- ext3 directory can have 32,000 sub-directories/files
  - Painfully slow to search
    - Just a simple array on disk (linear scan to lookup a file)
- ext4 replaces structure with an HTree
  - Hash-based custom BTree
  - Relatively flat tree to reduce risk of corruptions
  - Big performance wins on large directories – up to 100x

Approaches to Encryption (device)

- Block device encryption
  - Encrypt entire partition/disk
- Linux: dm-crypt
- Windows: BitLocker
- Mac: FileVault 2



Device Encryption Intuition

- File system is created on a virtual block device
- Low-level read of virtual block device:
  - FS requests block read into block cache page X
  - Map to block(s) on real device
  - Request that blocks be read into a temporary page Y
  - Decrypt page Y into page X
  - Return to file system
- Writes encrypt pages before sending to disk

Approaches to Encryption (filesystem)

- File system encryption
  - Encrypt between VFS/Block cache
- Linux: eCryptFS
- Windows: EFS
- Mac: FileVault 1

File System Encryption Intuition

- Mount layered file system over real one
- Application writes encrypted file ‘foo’
- Encrypted FS opens real file foo
  - Stores crypto metadata (like the cipher used) at the front
  - Transparently encrypts page in block cache

File System Encryption Intuition

- Read of file 'bar'
  - Encrypted FS asks real FS for file 'bar'
  - Uses metadata + secret key to decrypt
  - Stores decrypted pages in block cache
- Challenges:
  - Managing private keys
  - Enforcing read protection on decrypted data in block cache

Pros/Cons of Device Encryption

- Pros:
  - Hides directory structure, used space, etc.
    - Metadata matters!
  - Can put any file system on top of it
- Cons:
  - Everything encrypted with one key
    - No confidentiality between users on a shared system
  - Encryption overhead for public data (like /etc/hostname)

Pros/Cons FS Encryption

- Pros:
  - Per-user (or per directory or file) encryption
  - Only encrypt truly secret data
- Cons:
  - Harder to hide/obfuscate directory structure and metadata
    - Still possible with device encryption based on access patterns
  - More keys to manage