The Page Cache

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CSE 506

Recap

- Last time we talked about optimizing disk I/O scheduling
  - Someone throws requests over the wall, we service them
- Now: Look at the other side of this "wall"
  - Today: Focus on writing back dirty data

Holding dirty data

- Most OSes keep updated file data in memory for "a while" before writing it back
  - I.e., "dirty" data
- Why?
  - Principle of locality: If I wrote a file page once, I may write it again soon.
- Idea: Reduce number of disk I/O requests with batching

Today's problem

- How do I keep track of which pages are dirty?
- Sub-problems:
  - How do I ensure they get written out eventually?
    - Preferably within some reasonable bound?
  - How do I map a page back to a disk block?

Starting point

- Just like JOS, Linux represents physical memory with an array of page structs
  - Obviously, not the exact same contents, but same idea
- Some memory used for I/O mapping, device buffers, etc.
  - Other memory associated with processes, files
- How to represent these associations?
  - For today, interested in "What pages go with this process/ file/etc?"
  - Tomorrow: What file does this page go to?

Simple model

- Each page needs:
  - A reference to the file/process/etc. it belongs to
    - Assume for simplicity no page sharing
  - An offset within the file/process/etc
- Unifying abstraction: the address space
  - Each file inode has an address space (0—file size)
  - So do block devices that cache data in RAM (0---dev size)
  - The (anonymous) virtual memory of a process has an address space (0—4GB on x86)

Address space representation

- We saw before that a process uses a list and tree of VM area structs (VMAs) to represent its address space
- A VMA can be anonymous (no file backing)
  - Or it can map (part of) a file
- Page table stores association with physical page
- Good solution:
  - Sparse, like most process address spaces
  - Scalable: can efficiently represent large address spaces

Tracking file pages

- What data structure to use for a file?
  - No page tables for files
- For example: What page stores the first 4k of file "foo"
- What data structure to use?
  - Hint: Files can be small, or very, very large

The Radix Tree

- A space-optimized trie
  - Trie: Rather than store entire key in each node, traversal of parent(s) builds a prefix, node just stores suffix
    - Especially useful for strings
  - Prefix less important for file offsets, but does bound key storage space
- More important: A tree with a branching factor k > 2
  - Faster lookup for large files (esp. with tricks)
- Note: Linux's use of the Radix tree is constrained

A bit more detail

- Assume an upper bound on file size when building the radix tree
  - Can rebuild later if we are wrong
- Specifically: Max size is 256k, branching factor (k) = 64
- 256k / 4k pages = 64 pages
  - So we need a radix tree of height 1 to represent these pages

Tree of height 1

- Root has 64 slots, can be null, or a pointer to a page
- Lookup address X:
  - Shift off low 12 bits (offset within page)
  - Use next 6 bits as an index into these slots (2^6 = 64)
  - If pointer non-null, go to the child node (page)
  - If null, page doesn't exist

Tree of height n

- Similar story:
  - Shift off low 12 bits
- At each child shift off 6 bits from middle (starting at 6 * (distance to the bottom – 1) bits) to find which of the 64 potential children to go to
  - Use fixed height to figure out where to stop, which bits to use for offset
- Observations:
  - "Key" at each node implicit based on position in tree
  - Lookup time constant in height of tree
    - In a general-purpose radix tree, may have to check all k children, for higher lookup cost

Fixed heights

- If the file size grows beyond max height, must grow the tree
- Relatively simple: Add another root, previous tree becomes first child
- Scaling in height:
  - 1: 2^((6*1) +12) = 256 KB
  - 2: 2^((6*2) + 12) = 16 MB
  - 3: 2^((6*3) + 12) = 1 GB
  - 4: 2^((6*4) + 12) = 16 GB
  - 5: 2^((6*5) + 12) = 4 TB

Back to address spaces

- Each address space for a file cached in memory includes a radix tree
  - Radix tree is sparse: pages not in memory are missing
- Radix tree also supports tags: such as dirty
  - A tree node is tagged if at least one child also has the tag
- Example: I tag a file page dirty
  - Must tag each parent in the radix tree as dirty
  - When I am finished writing page back, I must check all siblings; if none dirty, clear the parent's dirty tag

When does Linux write pages back?

- Synchronously: When a program calls a sync system call
- Asynchronously:
  - Periodically writes pages back
  - Ensures that they don't stay in memory too long

Sync system calls

- sync() – Flush all dirty buffers to disk
- fsync(fd) – Flush all dirty buffers associated with this file to disk (including changes to the inode)
- fdatasync(fd) – Flush only dirty data pages for this file to disk
  - Don't bother with the inode

How to implement sync?

- Goal: keep overheads of finding dirty blocks low
  - A naïve scan of all pages would work, but expensive
  - Lots of clean pages
- Idea: keep track of dirty data to minimize overheads
  - A bit of extra work on the write path, of course

How to implement sync?

- Background: Each file system has a super block
  - All super blocks in a list
- Each super block keeps a list of dirty inodes
- Inodes and superblocks both marked dirty upon use

Simple traversal

```
for each s in superblock list:
    if (s->dirty) writeback s
    for i in inode list:
        if (i->dirty) writeback i
        if (i->radix_root->dirty) :
            // Recursively traverse tree writing
            // dirty pages and clearing dirty flag
```

Asynchronous flushing

- Kernel thread(s): pdflush
  - Recall: a kernel thread is a task that only runs in the kernel's address space
  - 2-8 threads, depending on how busy/idle threads are
- When pdflush runs, it is given a target number of pages to write back
  - Kernel maintains a total number of dirty pages
  - Administrator configures a target dirty ratio (say 10%)

pdflush

- When pdflush is scheduled, it figures out how many dirty pages are above the target ratio
- Writes back pages until it meets its goal or can't write more back
  - (Some pages may be locked, just skip those)
- Same traversal as sync() + a count of written pages
  - Usually quits earlier

How long dirty?

- Linux has some inode-specific bookkeeping about when things were dirtied
- pdflush also checks for any inodes that have been dirty longer than 30 seconds
  - Writes these back even if quota was met
- Not the strongest guarantee I've ever seen…

Mapping pages to disk blocks

- Most disks have 512 byte blocks; pages are generally 4K
  - Some new "green" disks have 4K blocks
  - Per page in cache – usually 8 disk blocks
- When blocks don't match, what do we do?
  - Simple answer: Just write all 8!
  - But this is expensive – if only one block changed, we only want to write one block back

Buffer head

- Simple idea: for every page backed by disk, store an extra data structure for each disk block, called a buffer_head
- If a page stores 8 disk blocks, it has 8 buffer heads
- Example: write() system call for first 5 bytes
  - Look up first page in radix tree
  - Modify page, mark dirty
  - Only mark first buffer head dirty

More on buffer heads

- On write-back (sync, pdflush, etc), only write dirty buffer heads
- To look up a given disk block for a file, must divide by buffer heads per page
  - Ex: disk block 25 of a file is in page 3 in the radix tree
- Note: memory mapped files mark all 8 buffer_heads dirty. Why?
  - Can only detect write regions via page faults

Raw device caching

- For simplicity, we've focused on file data
- The page cache can also cache raw device blocks
  - Disks can have an address space + radix tree too!
- Why?
  - On-disk metadata (inodes, directory entries, etc)
  - File data may not be stored in block-aligned chunks
    - Think extreme storage optimizations
  - Other block-level transformations between FS and disk (e.g., encryption, compression, deduplication)

Summary

- Seen how mappings of files/disks to cache pages are tracked
  - And how dirty pages are tagged
  - Radix tree basics
- When and how dirty data is written back to disk
- How difference between disk sector and page sizes are handled