Fine Grained Block Translation

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Some methods are released under the GPL.
The Benefits of Block Translation

- Block translation lets you change the nature of the IO workload that a device sees.
  - Convert random writes into linear writes
  - Lower the overhead and wear of parity RAID
    - ... to levels that are lower than mirroring
- Block translation is also required for:
  - Data reduction like compression and de-dupe
- ... But block translation can do a lot more
Block Translation

- We see frequent examples of using block translation with storage.
- How complex these techniques are largely depends on how “dynamic” the translation scheme is.
Static Layouts

- Static Layouts are common. These are layouts where the location of a block does not change and can instead be computed.
  - Partition Tables
  - RAID
  - LVM (sometimes)
Coarse Grained Dynamic Layouts

- Some layouts do move around as data changes. These solutions often involve large blocks to keep the management of the moves low cost.
  - Bad block re-mapping
  - LVM resizing
  - Copy on Write
    - LVM Snapshots
Medium Grained Dynamic Layouts

- Some solutions are in-between with a larger number of blocks that move around
  - ZFS
Fine Grained Dynamic Layouts

- Finally, some solutions are very dynamic with every block being re-positioned on every update.
  - SSD FTLs
  - Various proprietary mapping engines
Fine Grained Translation Layers are actually a Big Database Problem

- 40TB of storage is 10 Billion 4K blocks
  - Managing 10 billion of anything is non-trivial
  - Even as a simple flat table this is:
    - 34 bits x 10B = 42.5 GB
    - 5 bytes x 10B = 50 GB
    - 8 bytes x 10B = 80 GB
- The math for 400TB gets even worse
Choosing a Mapping Size

- 8 bytes entries seem ideal
  - Aligned for speed
  - Able to pack into pages
  - But the memory footprint is higher
- Bit alignment is tempting
  - Minimum memory usage
  - But you have to use a lot of shifts and locks to access entries
    - … probably not worth the trouble
- 5 bytes seems to be the sweet spot with current hardware
  - Unlike older systems, unaligned memory accesses no longer have the extreme performance hits of days past.
The Real Problem is Data Consistency Across a Crash

- We are updating two different data sets.
  - The data blocks
  - The map to the data blocks
- We cannot just update a RAM table
  - Something has to keep the two sets in sync
- The solution is “atomic updates”
Atomic Updates

- We want to write the data blocks and the control information that describes the data blocks in an “atomic update”.

Atomic Update Styles

- Journals
  - not great as we duplicate the writes
- In-place pointer updates
  - Not great as this breaks any chance of linearization
- Generation counters and in-place “journal like writes”
  - This is how we will get this to work
Flash back to 2005

- I did my first work on this in 2005
- My patents date back to 2007
- The goal as:
  - Single update maintaining perfect linearity
  - Move all of the overhead to mount
The On-Disk Update Structure

- So we get to dive into the actual update structures.
- First, the update “patterns”:
  - The disk is segmented into large “write stripes”
    - The stripes are large enough to keep the media and any underlying FTL happy.
      - This is typically 256 MB for SATA SSD, and 1GB for NVMe SSDs.
      - The media does not EVER have a write seek that is not aligned with these stripes.
  - The write stripes are further divided into “write buffers”
    - We do this so that our already large memory footprint does not go thru the sky
  - The write buffers are further divided into variable length “write segments”
    - These write segments are the “atomic update” structure
The Write Segment Structure

- At its simplest, the structure has:
  - A header
  - Some number of data blocks
  - Some number of meta tags that describe the blocks
  - Some CRC or Hash values to verify the data is intact
  - A footer
- This is the FBD v1 layout
## Atomic Update Segment Layout

<table>
<thead>
<tr>
<th>HDR</th>
<th>Meta Tag Array</th>
<th>Data Block</th>
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</table>

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What is in the Header?

- A signature
- The size of the segment
- The number of elements in the segment
- The generation counter for the write stripe
- A CRC or hash to ensure the segment is intact
What about Trim?

- This structure makes it very easy to implement trim/discard.
  - Leave the data block out
  - Output the meta array entry with bits that indicate all zeros or FFFFs
- Trim is amazingly fast, and has almost no wear
  - We routinely clock trim at > 500 GB/sec
This is Enough to Work Amazingly Well

- Mount is a bit slow, but safe
  - You have to ‘walk” every segment on this media
  - You don’t have to read the actual data blocks
- It is very space efficient with meta tags at only about 0.15% of space overhead
- It has size limits because of mount time
- It is not very extensible
Write Segment Optimization #1

- Summarize the meta array for each write block.
  - This keeps you from having to walk each segment.
    - Mount is typically “two reads” for each write block
    - You still have to walk the “tail write”, but there is only one of these.
  - You do lose an additional 0.15% of space
    - Trading space for time and memory will become a theme
- This pushes the practical array size to well over 200 TB
So Where Does This Get You?

- If you combine this write structure with an underlying optimized array you can reach:
  - Example 24 SATA SSD array running RAID-6
    - > 11 GB/sec writes at large blocks
    - > 2M 4K random writes
  - Negligible overhead on reads
  - Lowering of Flash Wear to near theoretical limits based on free space
What Does the Array Need to Do?

- The Array must be optimized for aligned writes to exact chunks
  - This is an ideal environment for erasure codes
  - Standard RAID-5/6 works very well if:
    - GPL patch for drivers/md/raid5.c with logic to avoid Read/Modify/Write cases
    - Patch also does parity calcs on calling thread, so you scale with cores.
  - 11+ GB/sec and 2M+ IOPS are for 24 SATA SSD running RAID-6
Things the Simple Layout Achieves

- All data blocks are 4K aligned
  - No extra copies
- Large writes are stored together
  - Subsequent read transfers are more efficient
- Chunks are typically small, making the array scale better
  - Large reads actually spread out across multiple SSDs in parallel
But We Can Go Beyond 4K

- While 4K only blocks are efficient, the “linear write” structure lets you do more
  - Step 1, compression
    - LZ4 Optimized for 4K blocks
      - > 1GB/sec/core by limiting dict size so that it fits in L1 cache
    - Pad compressed blocks to 64 byte boundaries
      - +12 bits in the lookup table
      - 6 bytes needed for up to 256 TB arrays
Write Segment with Compressed Blocks

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<td></td>
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</table>
Compression Overhead

- Significantly more CPU usage
- Some additional latency for low Q depth IO
- But is it still easy to reach “drive speed”
  - >11 GB/sec writes
  - > 2M IOPS on writes
Beyond Just Translating Blocks

- We can abuse the atomic write segment structure to create whole new solutions
  - Step 1, lower the memory requirements and lower the amount of time for a mount
    - This is necessary for really large arrays
    - This is necessary for dual-ported drives in HA/failover configurations
Embed Most of the LBA Table on Flash

- Place parts of the LBA table inside of the atomic write structure.
  - Each write will include a small LBA snippet that has lookups for 4, 8, or 16 LBA entries
  - This is not a “cache”
    - It is updated in real-time with the data blocks
  - Updating as few as four entries reduces the lookup table DRAM requirements by 75%
Turning the LBA Table Into a Shallow Tree

- The LBA “snippets” are very small
  - They don’t add much to write overhead
  - They have little impact on Flash capacity.
- We can push this further by writing a “mini tree”
  - 2.5% of flash space overhead (worst case)
  - 1:256 DRAM usage reduction
LBA Table Lookup Tree
LBA Trees

- 40TB – we would typically need 10B entries
  - 60 GB of ram at 6 bytes/per entry
  - 1/256 of space needed – 240 MB
    - Each level is 6 bytes * 4 – 24 bytes
    - Each random write uses 96 extra bytes of storage (2.5%). Linear writes use less.
    - Nodes are easy to cache as 6 byte is enough to double as a disk or RAM pointer.
  - Only the top-level has to be mounted. The rest can be demand paged (although perhaps we need another word than “paged”).
Extended Write Segment Structure

- Master Header – total sizes, counts, and generation tags
- Sub Headers, one for each type of data
  - Block data
  - Meta tags used on mount
  - Meta tags used on defrag (GC)
  - CRC arrays used for data validation
    - We still use summary meta arrays for each write block
- Mount can now read a fraction of the array
  - Enables support for “huge” arrays
  - Enables fast mounts that are quick enough for “HA Failover”
What can we use “low memory” for?

- Lowering system cost.
- De-dupe with high data reduction ratios
  - De-dupe needs:
    - LBA to Block ID translation
    - ID to actual data translation with reference counters
  - The LBA entries are most of the space, but they have high “locality” so they cache well.
  - The Block ID entries are hashes, so they need to have committed memory or else you will pay with a read on every access.
And finally, what about “beyond blocks”?

- So far, we are just storing someone else’s blocks.
- We can map many LBA “numbers” to storage objects.
  - The objects can be variable sized.
  - The object can also be compressed.
  - Different types of objects can be mapped in different name spaces.
  - The LBA ranges are “thin provisioned” which makes file system design easier.
  - The LBA tables themselves are “allocation bitmaps”
So, Let's Build a File System

- This is unlike any file system you have ever seen.
  - It has no real concept of a “page”
  - It is optimized for “object access”, but still allows in-place updates.
- Most file creates require fractional IOs.
- Directories above 1 billion entries are practical
- Space utilization for small files is > 90%.
The WildFire File Sysytem

- Some of this actually has been implemented
  - i.e., a single directory that can do creates, reads, and scans, and deletes.
    - Here are the “block namespaces” used so far.
      - Block type 1: Directory Control
      - Block type 2: Directory extents
      - Block type 3: Directory groups
      - Block type 4: Small File contents
      - Block type 5: File extends
      - Block type 6: Random access file blocks
      - Block type 7: Object file blocks
But What are the Block Limits?

- If you push the “block pointer” to 8 bytes, you can point to a block with:
  - Up to a 16 PB array
  - Variable sizes from 16 byte to 1 MB with compression
  - … or 64 MB without compression
    - Point to the local array, or off-array (perhaps to spinning media for large objects)
So What Does a Directory Look Like?

- Each directory has a single, small control block with counters.
  - This gets updated a lot. Because it is small, the overhead on disk wear and bandwidth is low.
  - There is an “extents” block that maps to groups.
Groups and Variable Sized Blocks are Meant for Each Other

- Groups are added and removed dynamically, but still use hashes for lookups
  - This involves hashes to a binary modulus and single group split/merges as files are created and removed
- Groups will vary in fill level, but the variable sized blocks map this perfectly.
  - Space utilization is excellent
  - … which also translates to efficient use of disk IO bandwidth
What Kind of Performance Can you Get?

- When running “from disk” (ie, nothing in cache)
  - Each file open is a single direct read
  - Each file write is a single read, and then a merge/update of the group
    - The write itself is a part of the coalesced “write stream”, so it is very low overhead.
    - Unless there is a split, then there are updates to two blocks.
What Kind of Performance Can you Get?

- There is “no page cache”
  - Writes go directly into the “write segment” buffer
  - The “write segment can merge multiple requests before an actual update goes out.”
Small File Performance

- These were run on a Core-i7 VM with a single SATA SSD.
  - Create small files in a one directory
    - < 4 uSec per file create for 100K
    - < 7 uSec per file create for 4M
      - 2 uSec of this is VFS
  - 4x – 10x faster than EXT4
  - 8x – 30x faster than XFS
  - “Lots” faster than ZFS
Small Files as Objects

- Small files don’t really need extents
  - You can store “very little” files with their directory entries
  - You can store “bigger” files with their data in a single variable sized block
  - Optimized for files that are created “all at once”
    - But still support random and append files
Small Files as Objects

- This design is “built for speed”
  - Minimize IO with direct access to the data
  - Keep the data structure tight
    - All direct RAM links
    - Count “cache line misses”
    - No BTREEs or other slow lookups
    - No allocation bitmaps
    - All data is written “exactly once”
      - No journals
Really Big Directories

- 1 billion item directories are practical
  - It is easy to sustain creates at 2500/sec, single thread
  - Under 5 days for 1B file creates
    - vs 20 months for EXT4 and 6 years for XFS
    - … and even longer (actually much longer) for ZFS
- While everyone talks about file systems “without limits”, the limit that matters most is “time”
Incredible Space Efficiency

- 1 billion 100 byte files with 20 byte file names
  - About 200GB of space used with WFFS
  - About 5 TB of space used with EXT4/XFS
- … and it all works because you are translating block addresses.
But Why Is Block Translation Needed for a File System?

- Block Translation keeps the design simple
- Space management can happen in the background
  - This allows for defrag (GC)
- Thin provisioning of block addresses lets you assign large linear ranges when needed or individual blocks when needed.
- The atomic update structure is not an “extra write”.
- Writes are nearly 100% actual data with no pad.
Fine Grained Block Translation

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