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ZFS Caching

Explain Like I'm 5: the ZFS ARC (Adaptive Replacement Cache)

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Summary & Introductions

1 **Allan Jude**
FreeBSD Core Team
OpenZFS Developer

2 **Klara Inc.**
FreeBSD Professional
Services and Support

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Covered in this presentation

What is ZFS? Why all the excitement?	How does most caching work?	What is an ARC and why do I want one?	How does compression help me?

What is ZFS?

- ZFS is a filesystem with a built in volume manager
- Space from the pool is thin-provisioned to multiple filesystems or block volumes (zvols)
- All data and metadata is checksummed
- Optional transparent compression (LZ4, GZIP, soon: ZSTD)
- Copy-on-Write with snapshots and clones
- Each filesystem is tunable with properties

Why All The Excitement?

- Copy-on-Write means snapshots are consistent and instant
- Blocks used in snapshot(s) kept when overwritten/deleted
- Snapshots allow access to filesystem at point-in-time
- No performance impact on reads/writes
- Take no additional space until blocks change
- Makes your storage ransomware-resistant
- Clones allow you to “fork” a filesystem

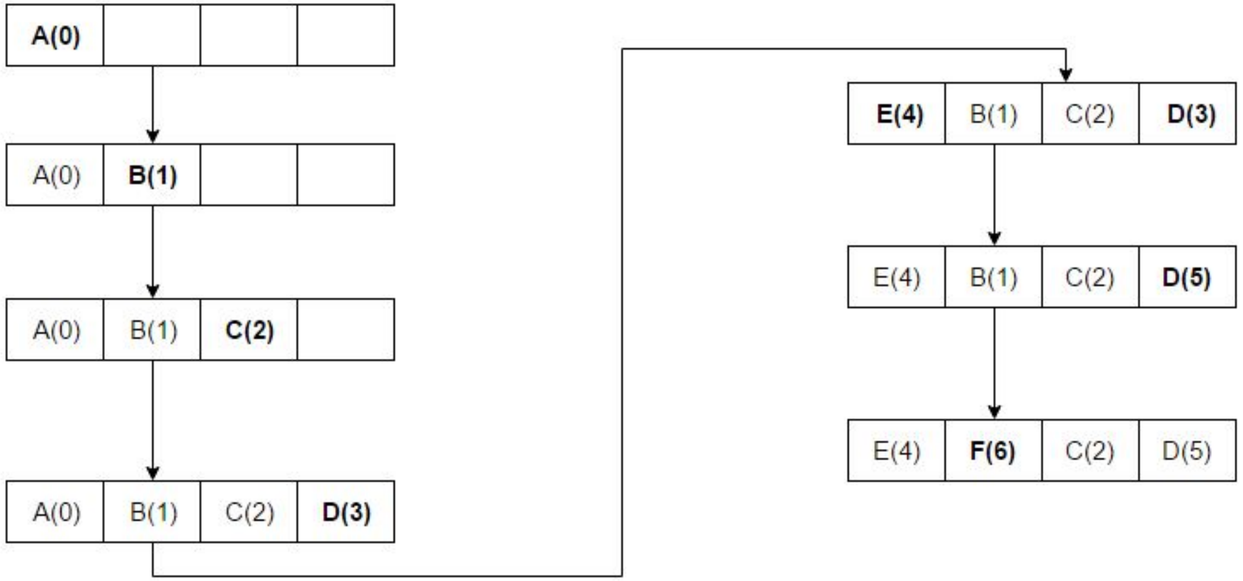
How Do Computers Work?

- Computers have multiple tiers of storage
- Each has different characteristics (speed, latency, capacity, durability)
- CPU L1 > L2 > L3 > RAM > NVDIMM > Disk Cache > Disk
- "We are therefore forced to recognize the possibility of constructing a hierarchy of memories, each of which has greater capacity than the preceding but which is less quickly accessible." Von-Neumann, 1946.

What Is a Cache?

- Copy of commonly and/or recently used data on faster storage
- This data can be discarded at any time, it is just a copy
- The amount of storage available in the faster tier is limited
- Faster/closer storage is a precious resource
- Need a caching algorithm to determine what to keep in cache
- Algorithm: LRU (Least Recently Used) from 1965 or earlier
- Free RAM is wasted RAM!

LRU: A B C D E D F



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LRU: Pros and Cons

- Usually double-linked list
- Low overhead
- Locality principle: if process visits memory location, likely to revisit location or neighborhood soon

- Ignores frequency
- Does not adapt over time
- Disrupted by large scans
- Does not consider recent history more heavily

LFU: Least Frequently Used

- Same idea as LRU, except instead of keeping a timestamp we keep a hit counter. Designed in 1971
- Each time we access a page, we increase the hit counter
- When cache is full, evict the page with the lowest counter
- Unlike an LRU, scanning a database or backing up a filesystem will not thrash the cache. The infrequently accessed objects will cycle through the cache without dislodging frequently accessed pages

LFU: Pros and Cons

- Immune to large scans
- Provides best performance for hot spots
- Advanced locality principle: probability of revisiting location increased with number of visits

- Logarithmic complexity (slower to update)
- Does not consider recency
- Accumulates data you are no longer using

Adaptive Replacement Cache (ARC)

- Proposed in 2003 by Dr. N. Megiddo & Dr. D. Modha
- Combines the best of LRU and LFU, plus some novel tricks
- The cache size (c) is partitioned (p) into two sections
- At the start, p = ½ c, first half of the cache is LRU, second LFU
- In addition to the two caches, there is a “ghost” list for each
- Each time an item is evicted from either cache, its key (but not its data) moves to the ghost list for that cache

Adapting the ARC

- There are 4 lists, the LRU, LFU, and their respective ghost lists
- When a page is requested and is resident in the LRU or LFU: this is a hit, data is retrieved from the cache, good job!
- The page has now been accessed frequently, moves to the LFU if not already there. If it is, LFU counter is incremented
- When a page is requested and it is not resident in either cache, this is a miss, better luck next time! Welcome to LRU.

Robbing Peter to Pay Paul

- When a page is requested and it is on one of the ghosts lists: If only that particular cache had been a little bit bigger, this would have been a hit. We were so close...
- If the hit is on the LRU ghost list, increment p, making the LRU larger, and the LFU smaller. We'll get it right next time!
- If the hit is on the LFU ghost list, decrement p
- The value of p constantly change to move towards the best mix of the LRU and LFU algorithms as your workload changes

A Whole Second (Optional) ARC

- Remember back at the beginning of this talk, tiered storage?
- The ARC is RAM, so it is fast, but you only have so much RAM
- There are devices faster than your main storage though…
- L2ARC (Level 2 ARC) uses a small amount of RAM to point to data on a high speed storage device (SSD, NVMe, NVDIMM)
- As data nears bottom of the LRU/LFU, it is copied to L2ARC
- Instead of being evicted, replaced with reference to L2ARC
- To avoid large scans, wearing out flash, fill rate is limited

Compressed ARC

- OpenZFS has transparent compression (LZ4, GZIP, ZSTD*)
- This will compress data before it is written to disk, if beneficial
- In the past, blocks were decompressed and then cached
- In 2016 George Wilson changed to deferred decompression
- Each time a block is read from cache, it is decompressed again
- LZ4 decompression is 2-10 gigabytes/sec/core
- Most users saw 50-200% increase in effective cache size

Not Quite That Easy

- The ARC handles filesystem data and metadata separately
- By default, metadata is limited to 25% of the cache
- Data can not be evicted if it is in use
- The ARC is not a fixed size, it has a minimum and maximum size, and adapts between them based on memory pressure
- The original ARC algorithm assumes fixed size pages, ARC blocks can be anywhere from 512 bytes to 16 MB

ARC vs Swapcache

- There are many memory compression schemes out there
- The general idea is to compress infrequently used memory to create additional free memory (conserve space)
- Reacting when the system is under stress is less optimal
- Compressed ARC is using compression to create more cache
- Compressed ARC takes advantage of compression you were already doing anyway, decompression is faster and cheaper
- Free memory is wasted memory

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Tuning the ARC

- Fileserver: Large ARC, increase metadata cache, L2ARC?
- Block Storage (iSCSI): Large ARC, select correct volblocksize
- Database (A): Small ARC, Cache only metadata, use DB buffer cache (understands usable better)
- Database (B): Medium ARC, small DB buffer cache, high compression ratio ARC gives higher hit ratio
- Hypervisor: Small-Medium ARC, reserve memory for VMs (don’t fight w/ ARC), avoid double caching (VM / host)

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QUESTIONS

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More Resources

- Want to know more about ZFS?
  - "FreeBSD Mastery: ZFS" & "FreeBSD Mastery: Advanced ZFS"
  - Not just for FreeBSD, DRM-Free ebooks ZFSBook.com
- BSDNow.tv - Weekly video podcast on BSD & ZFS
- @allanjude on twitter
- Want more? PapersWeLove.org "ARC after Dark":
  - https://www.slideshare.net/bcantrill/papers-we-love-arc-after-dark
  - https://www.youtube.com/watch?v=F8sZRBdmqc0