Building a Production Storage System in Practice

Architecture, Design, and Beyond

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Thanks to Eric Knauft for some slides I’ve borrowed from him.

About Myself

- Ph.D. in CS in 2004
- Joined Apple in 2004, led:
  - File Vault 2
  - Fusion Drive
  - File Vault Everywhere
- Joined vSAN team of VMware (now Broadcom) in 2014, led:
  - vSAN OSA End-to-end checksum
  - vSAN OSA Data-at-rest encryption
  - vSAN ESA
  - vSAN File Service
  - vSAN Object Service
  - Multiple internal productivity projects
- 178 granted patents

- In my free time
  - Exercise (Olympic weightlifting, zone 2, HIIT)
  - Books (economics, physics, math, business, health, fiction, and many more)
  - Study investment tips and share them on YT

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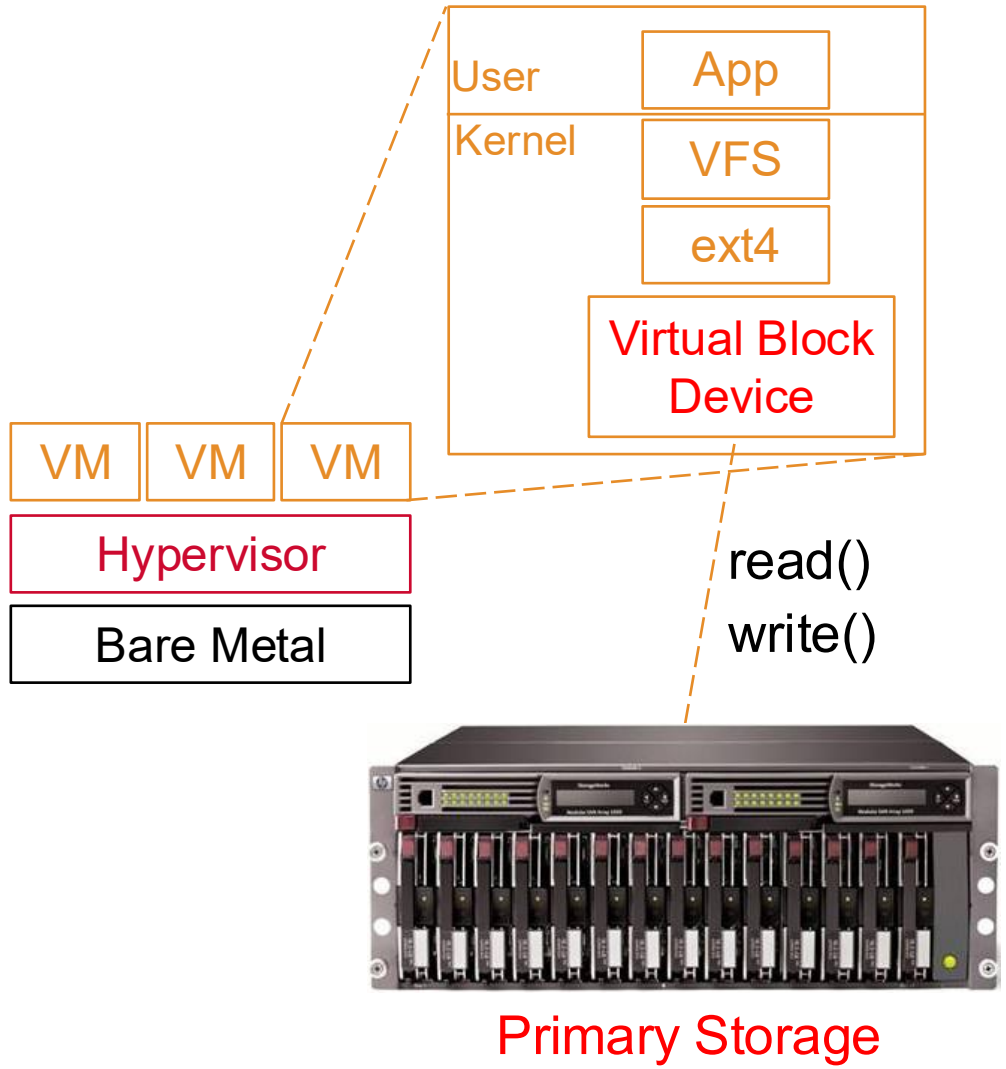
Storage in Data Center Infrastructure

- Applications run on “computers”, which can be:
  - Physical box (bare metal)
  - Virtual machine (VM)
- VMs run in Hypervisor (ESXi, KVM, …)
- The virtual “block device” backing the file system (e.g., ext4, NTFS) is the “Primary Storage”
- It provides a Block Interface:
  - Read N blocks at a block address
  - Write N blocks at a block address



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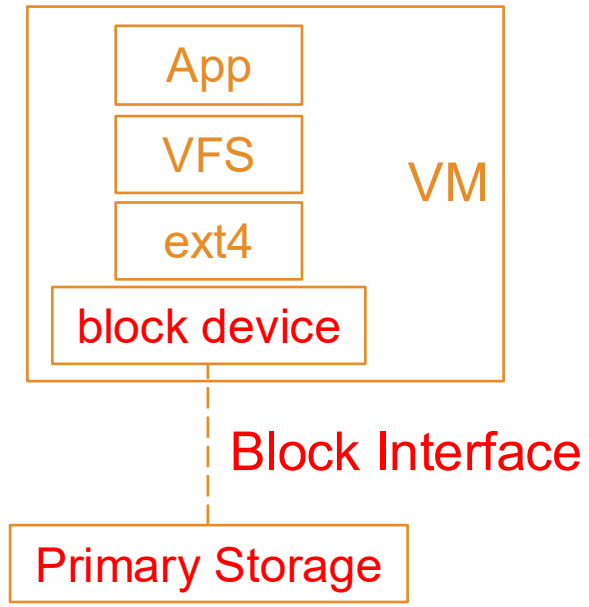
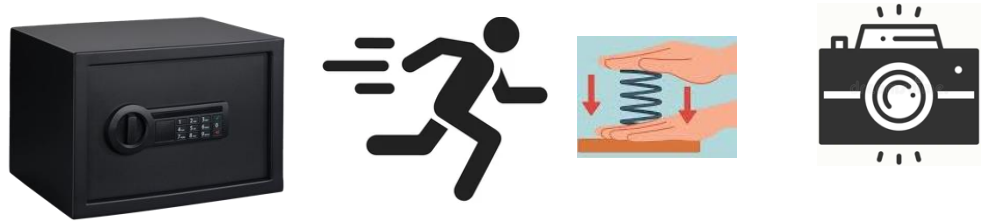
Key Features of Primary Storage in Data Centers

- Safe
  - Crash resistance
  - Fault tolerance
  - Checksum verification
- Fast
  - IOPS
  - Throughput
  - Scalability
- Cheap
  - Space saving: compressing, deduplication
- Other
  - Backup/restore: snapshot
  - …





Safe Fast Space Efficient Snapshot

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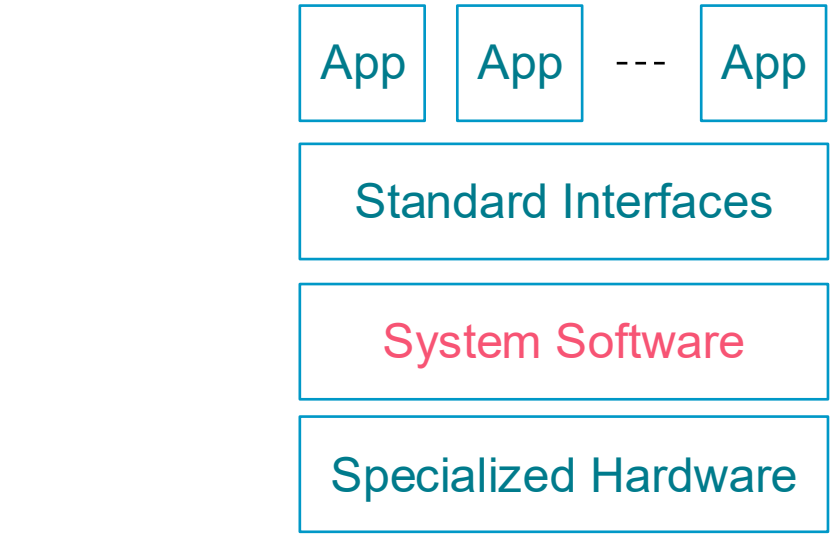
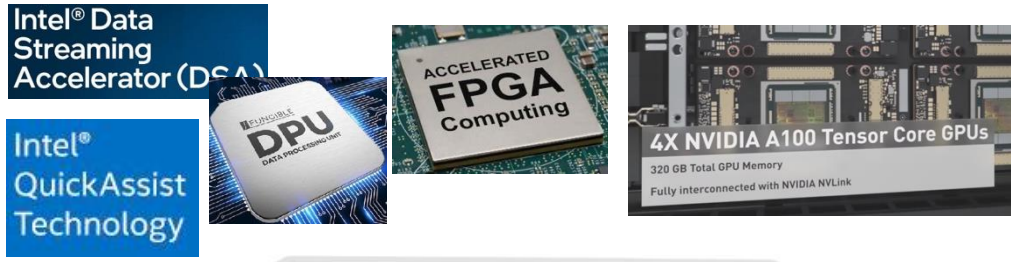
Technology Trends for System Software

- Old hardware trend: Moore's law
  - Faster, cheaper, higher capacity, lower power consumption
- New hardware trends
  - Specialization
    - DSA, QAT, DPU (SmartNIC), FPGA, GPU, …
  - Disaggregation
    - Compute-Storage disaggregation: NVMe-oF + JBOF
    - CPU-Memory disaggregation: CXL + RDMA + Remote RAM
- Interface trends: growing but standardized
  - Block, file, object
  - MySQL (TiDB), Postgres (CockroachDB, YogabyteDB)
  - Redis (MemoryDB, KeyDB, Tair)
  - Kafka (RedPanda)
  - …
- System software hides hardware differences and provides a standardized interface





JBOF

Principles of Developing System Software

- Takes a long time to develop & stabilize
  - Long term maintainability is important
  - Some over-engineering
  - Important to reuse
- New hardware changes:
  - Possible features
  - Bottlenecks
  - Architecture and design
- Performance is important
  - Higher consolidation ratio → saving money

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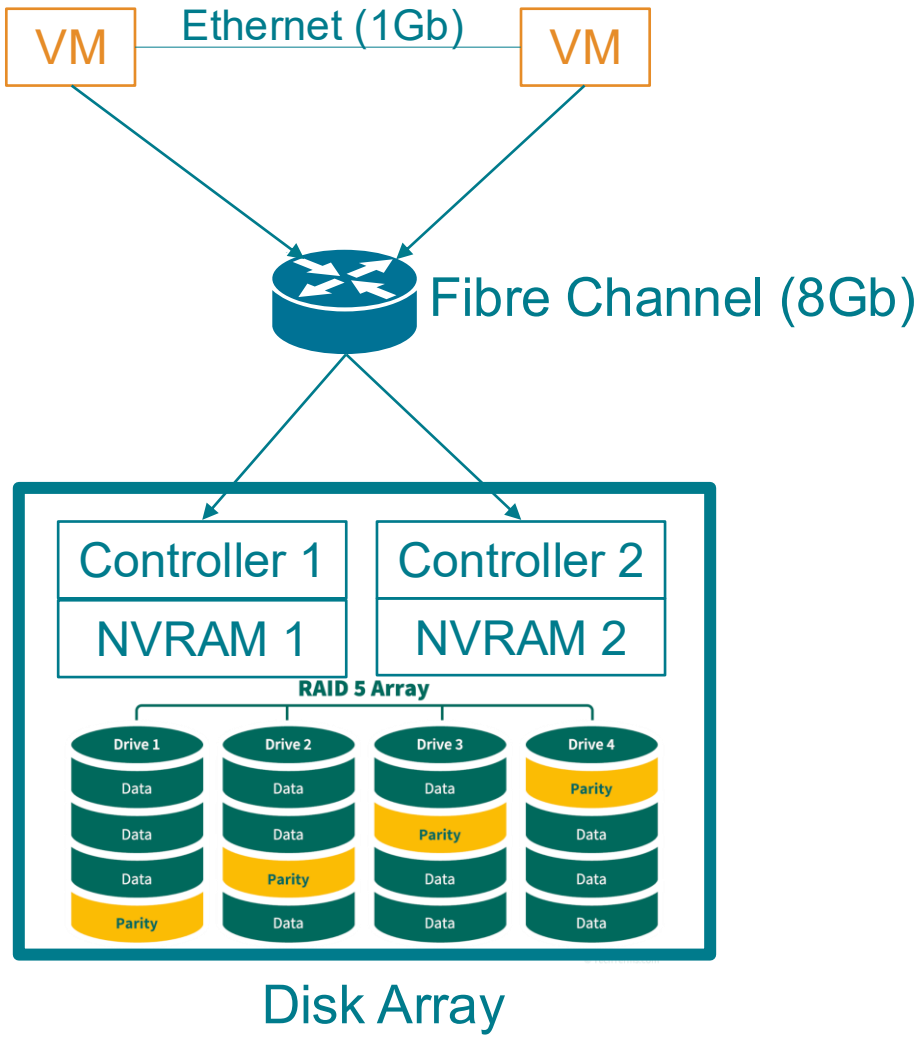
Disk Array – Storage Before vSAN

- External disk arrays
- Fault tolerance
  - Erasure coding or mirroring
  - Dual controllers
- Custom storage network
  - Fibre Channel
  - SAS
- Customized box
  - NVRAM
  - Dual controllers
- Expensive
- Hard to scale beyond one box



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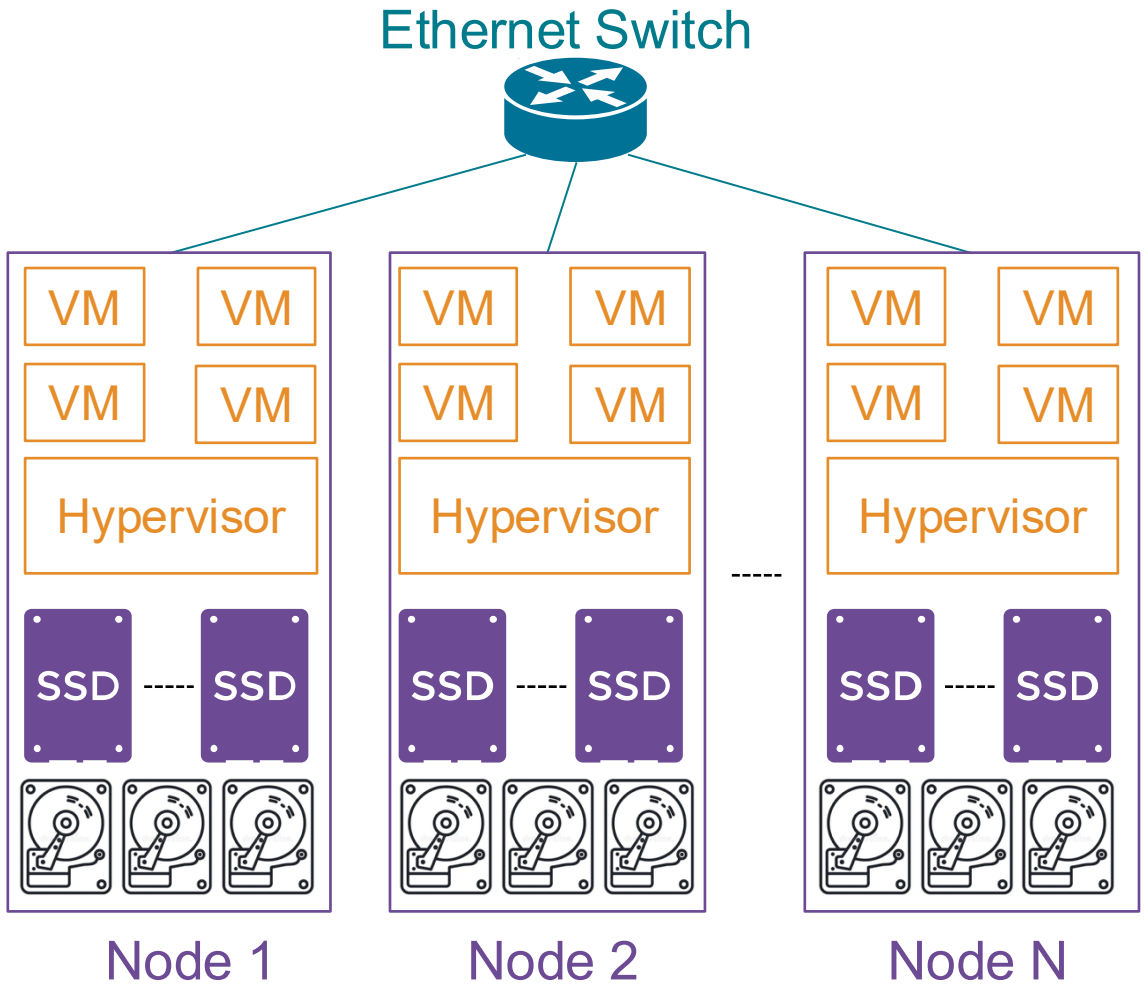
What is vSAN and Why It's Viable?

- Software-defined storage
  - Turns locally attached storage into a virtual disk array
  - Distributed erasure coding
- Benefits
  - Commodity hardware (cheap)
  - Scale-out architecture
- What hardware change made vSAN possible? In 2010
  - Fast SSDs (SATA SSD) – replaces NVRAM
  - Fast and cheap Ethernet – replaces FC
    - 10GbE caught up with Fibre Channel



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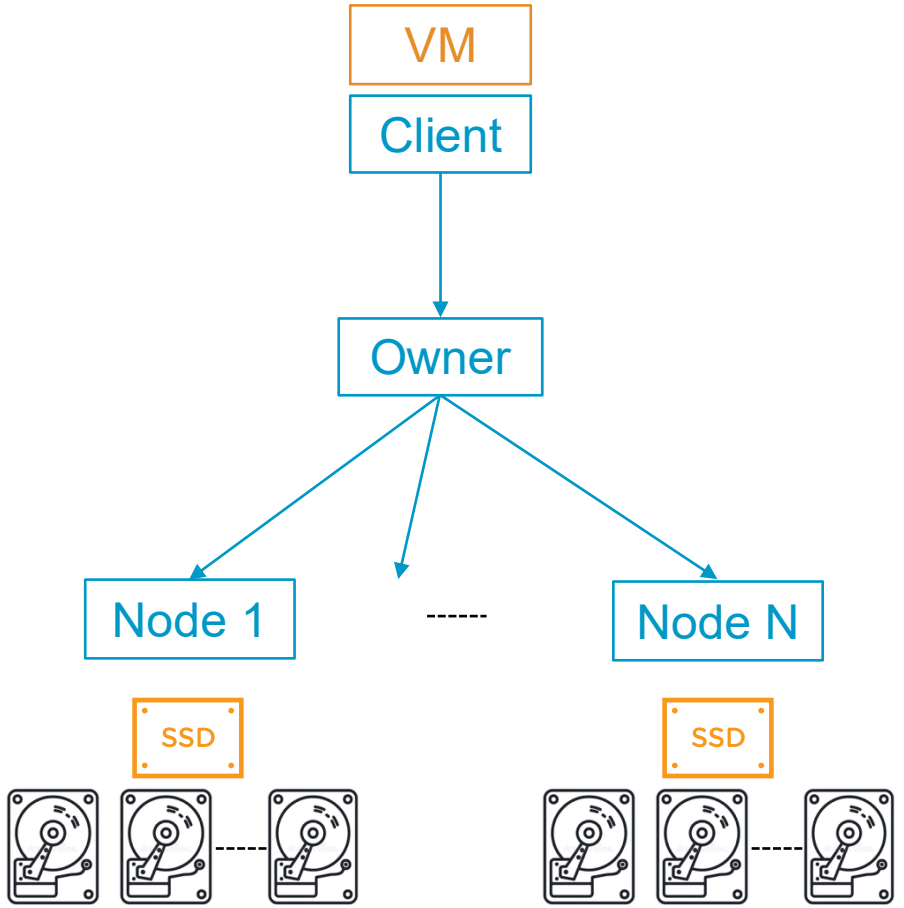
vSAN OSA (Original Storage Architecture) Architecture

- Scale-out
  - Nodes are connected via Ethernet
- Erasure coding cross hosts
- Local file system:
  - SSD Performance Tier
  - HDD Capacity Tier



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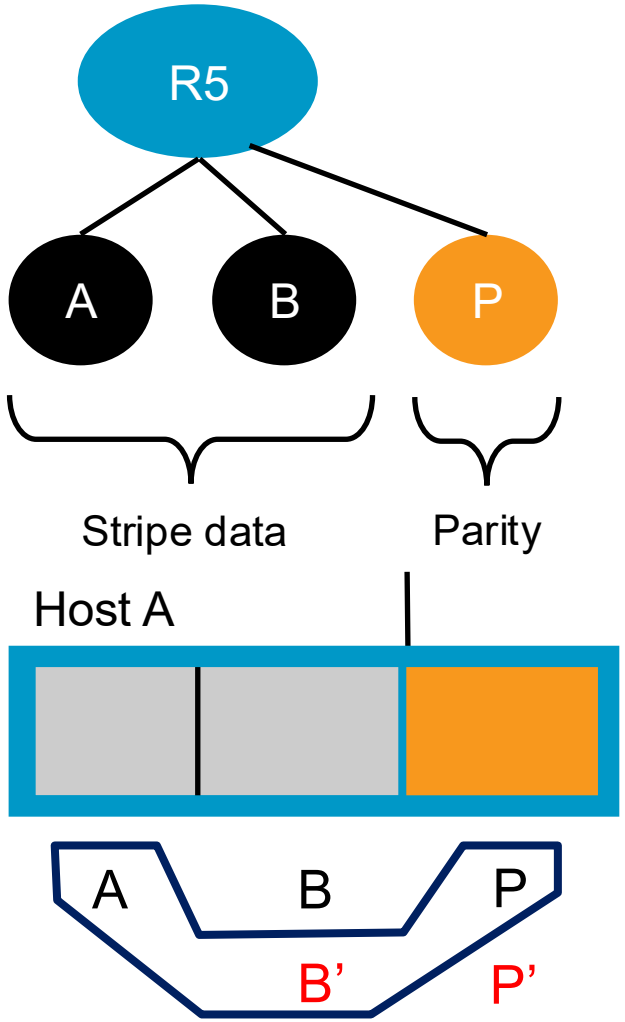
Distributed Erasure Code

- E.g., 2 + 1 RAID-5 or 4 + 2 RAID-6
- Parity: P = A ⊕ B; P’ = A ⊕ B’;
- The “Write Hole” problem
  - Update multiple blocks on different hosts atomically
- **Question**: if it crashes before P’ is written, what happens?
- Data corruption for A & B’
- **Question**: How to solve the write hole problem?
- Distributed transaction (two-phase commit)



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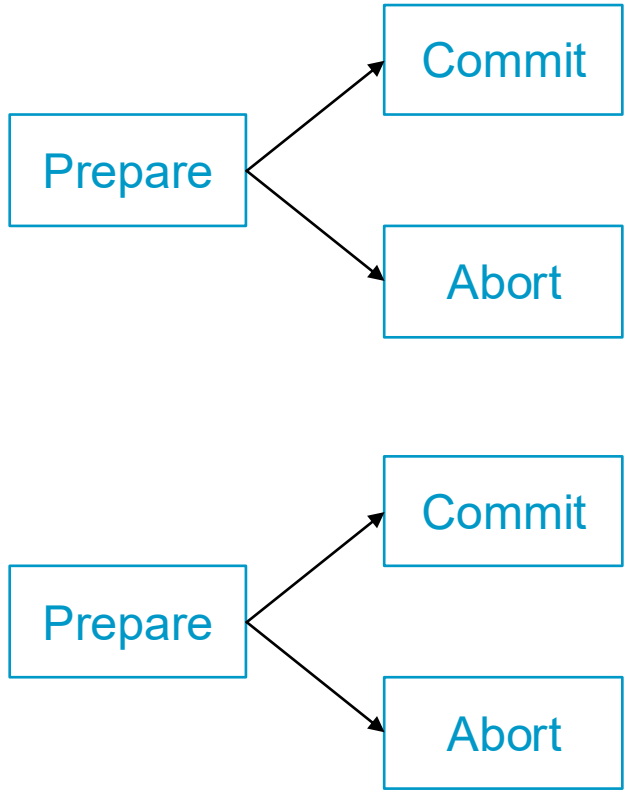
Two-phase Commit

- Algorithm:
  - Ask all parities to “Prepare”
  - If any party can’t Prepare: Abort all
  - If all parties can Prepare: Commit all
- **Question**: How to reduce network round trips?
  - Use “presumed commit”
- Happy path
  - Waits for all hosts to prepare
  - ACK the write to the client
  - Batch commit all txn < N later



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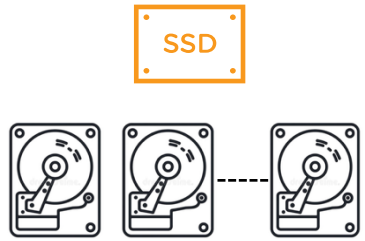
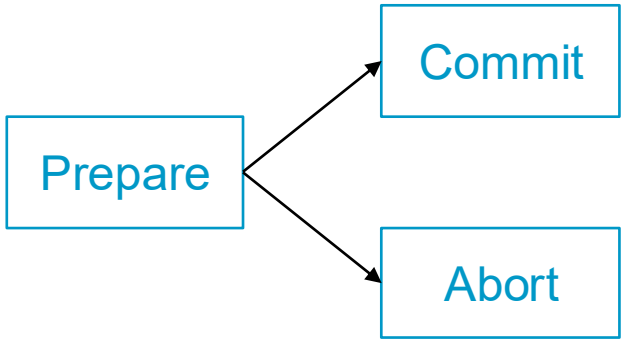
The Local File System

- Manages a disk group:
  - 1 SSD and N HDDs
- Basic features
  - Large files
  - Flat namespace (no directories, no file names)
- Must support 2PC (Prepare, Commit, Abort)
- **Question**: can “Prepare” cache data in memory only?
- Prepare must persist data
  - Can commit after prepare even after a power loss
- **Question**: can conventional file systems, such as ext4 or NTFS, be used to support 2PC?
- No, because “Prepare” can’t overwrite old data
  - Can’t abort if old data is overwritten





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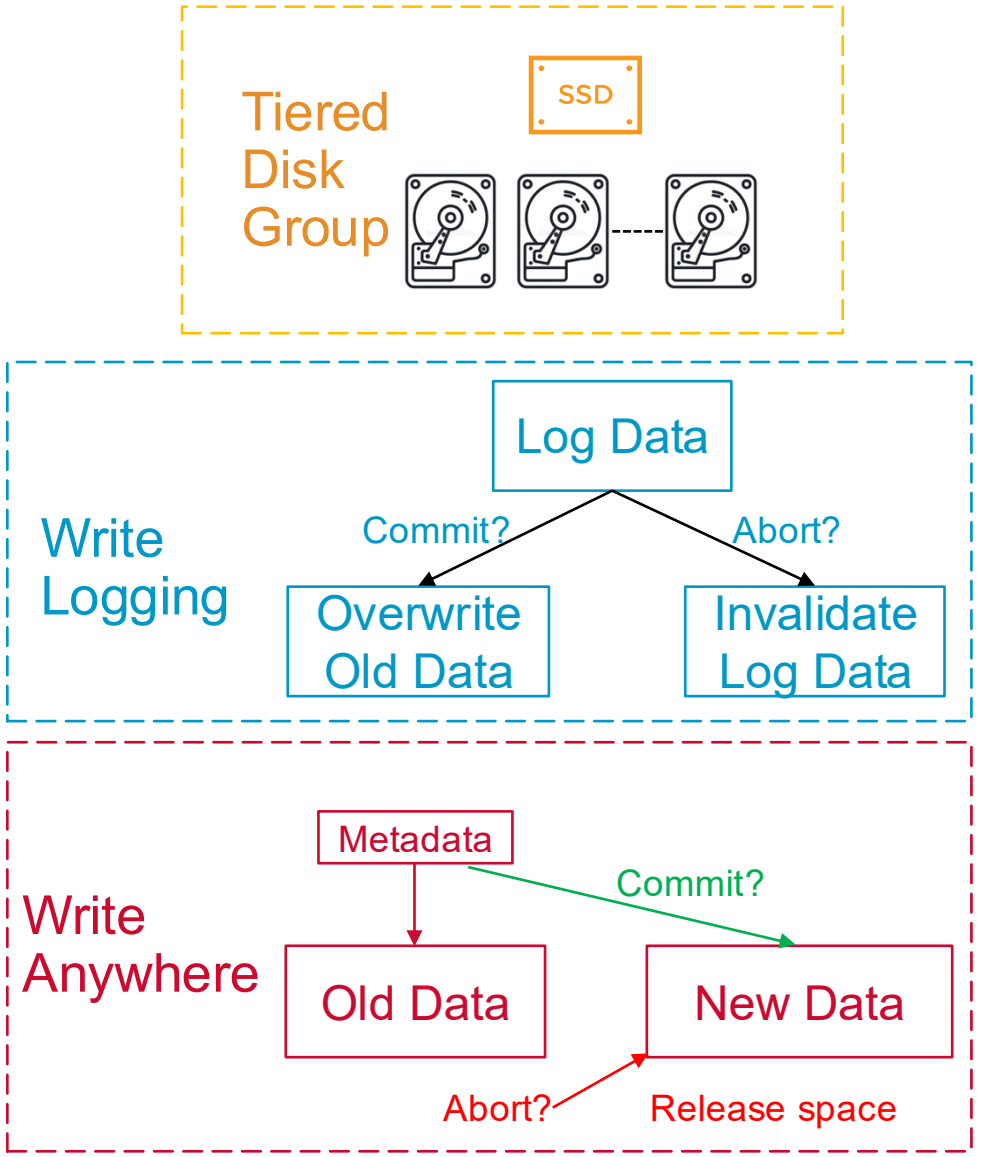
Two-phase Commit in File System

- File system has two tier: SSD and HDD
- Support Prepare, Commit or Abort
- Two choices
- Write logging
  - Log the prepare, overwrite later
  - Write twice
- Write anywhere
  - Write to new location, adjust metadata and delete old data later
  - Write once
- **Question**: which one works better?
- vSAN OSA uses write logging
  - Log to SSD and flush to HDD after commit
  - SSD also serves as a “Read Cache”



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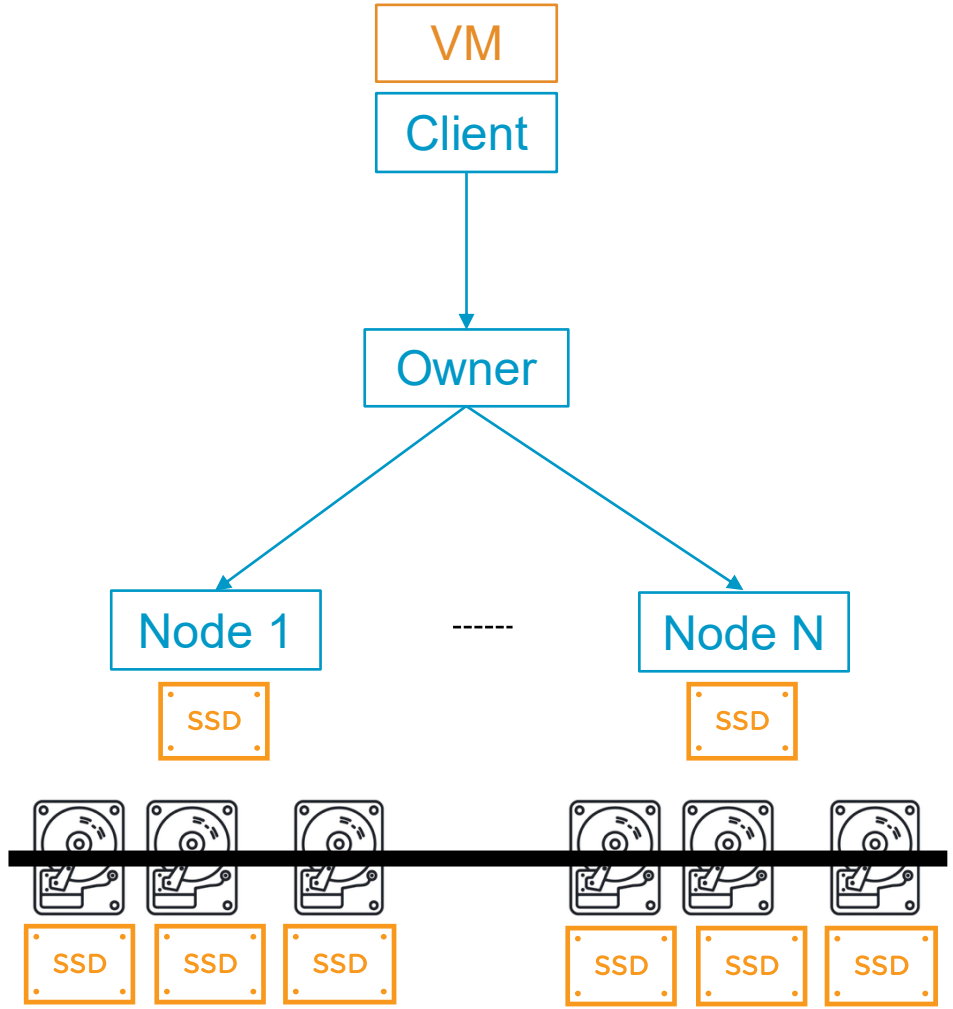
Evolving vSAN OSA

- OSA was a very fast HDD disk array
- Until
- SSDs become bigger, faster, and cheaper
  - SSD latency is more predictable than HDD latency
- Replaced HDD with SSD
- **Question**: What are potential performance problems of this change?
- Hints:
  - Performance goal: close to hardware limit
  - SSDs have similar performance



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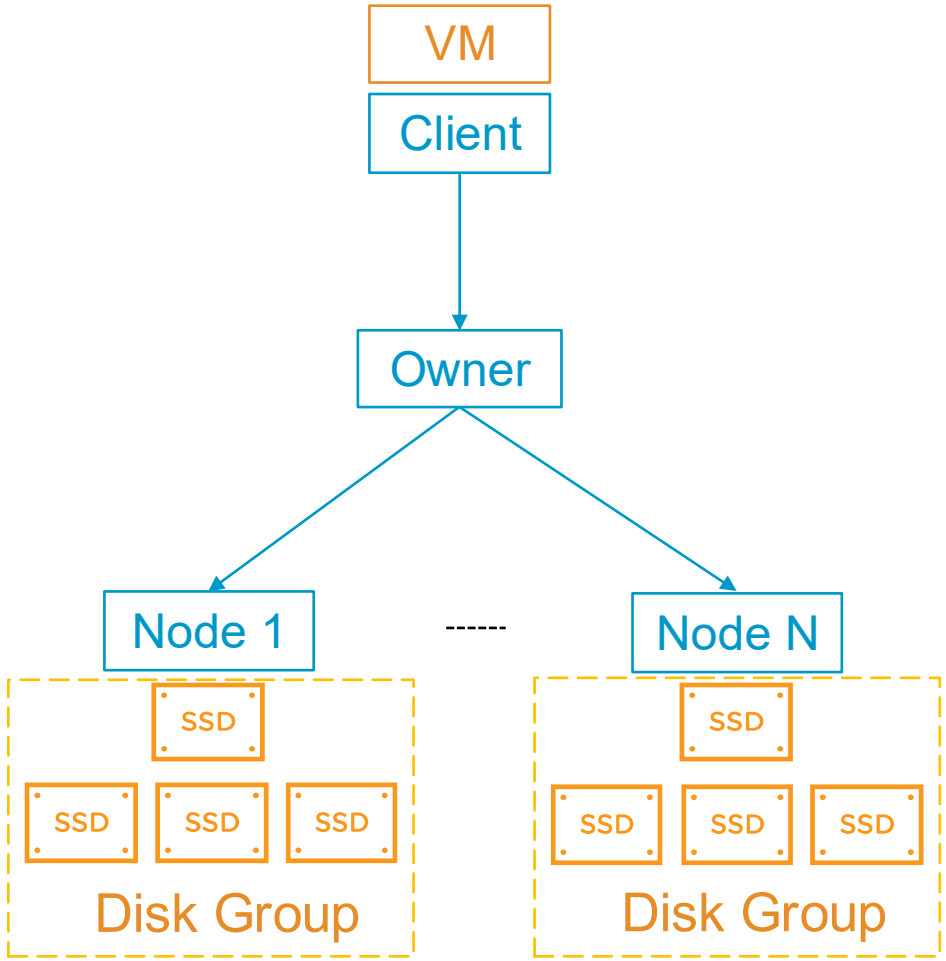
vSAN OSA Problems

- New bottleneck: Performance-tier SSD
  - On reads
  - “Read Cache” on performance-tier is slow
  - **Question**: how to solve this?
  - Disable the Read Cache
- New bottleneck: Performance-tier SSD
  - On large writes
  - File system’s “write logging” is slow
- New bottleneck: CPU
  - On small I/Os
  - Lack a multi-threaded architecture
- Old problems:
  - No good snapshots nor compression
  - Small writes are slow due to **partial stripe writes** on RAID-5 and RAID-6



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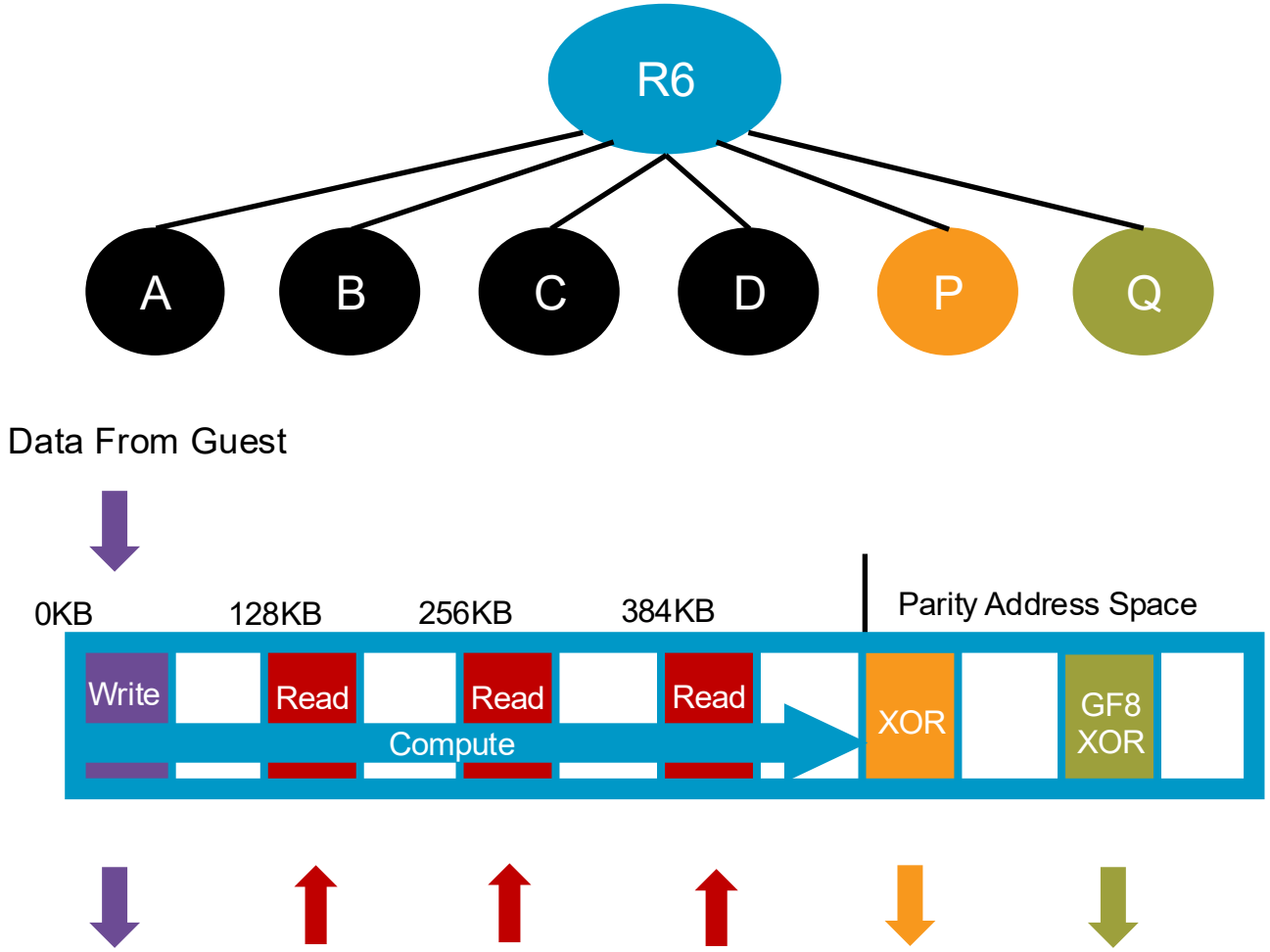
Partial Stripe Write

The Difficulty With RAID6

- Write A:
  - Read B C D, verify checksum
  - Calculate P and Q
  - Write A, P and Q
  - 1 Write ➔ 3 read, 3 writes
    - 6x amplification
    - 2 network round trips



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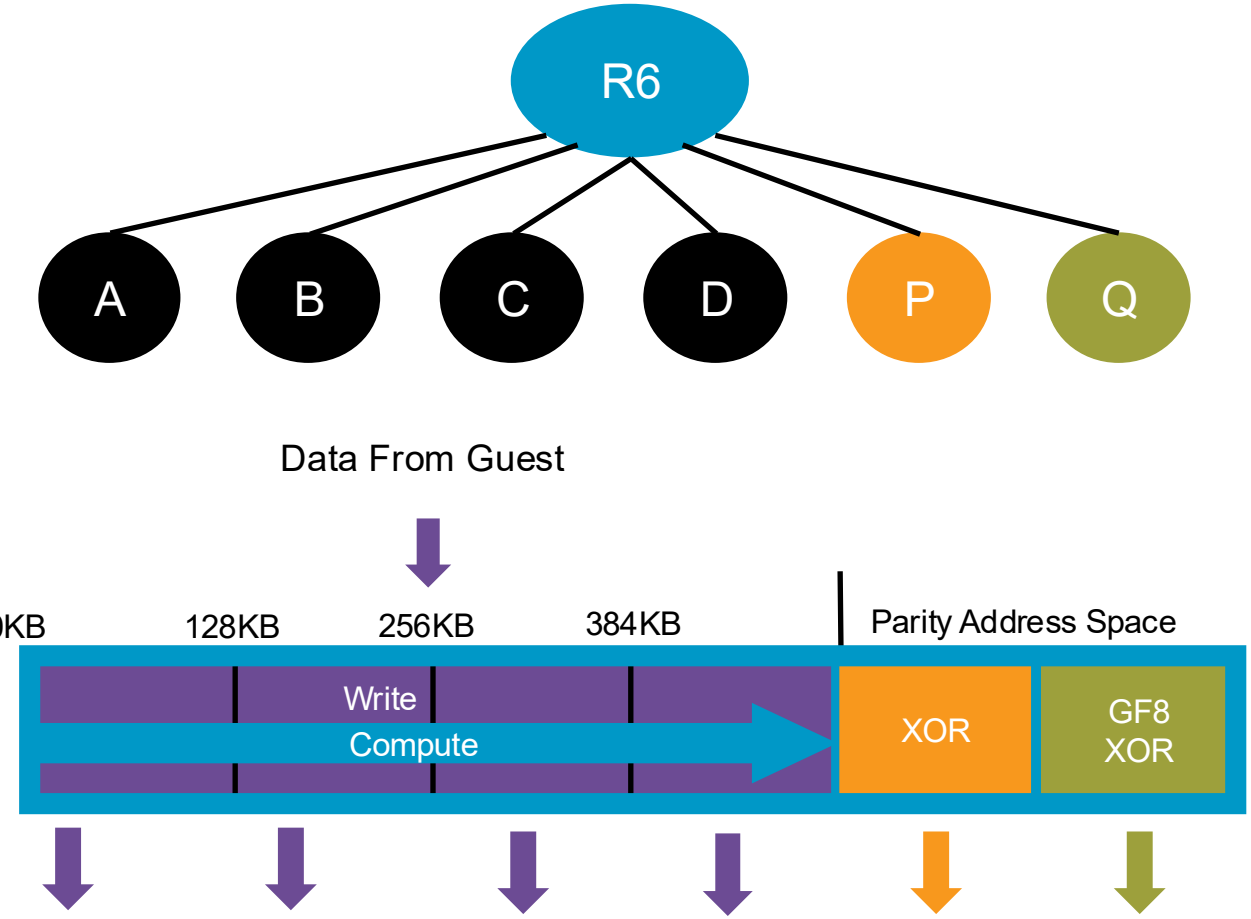
Full Stripe Write

Efficient Writes With RAID6

- Write A-D
  - Calculate P and Q
  - Write A-D, P and Q
  - 4 writes ➔ 6 writes
    - 1.5x amplification
      - 4x less IO than partial stripe
    - 1 network round trip
      - 2x less latency than partial stripe



Large writes are faster

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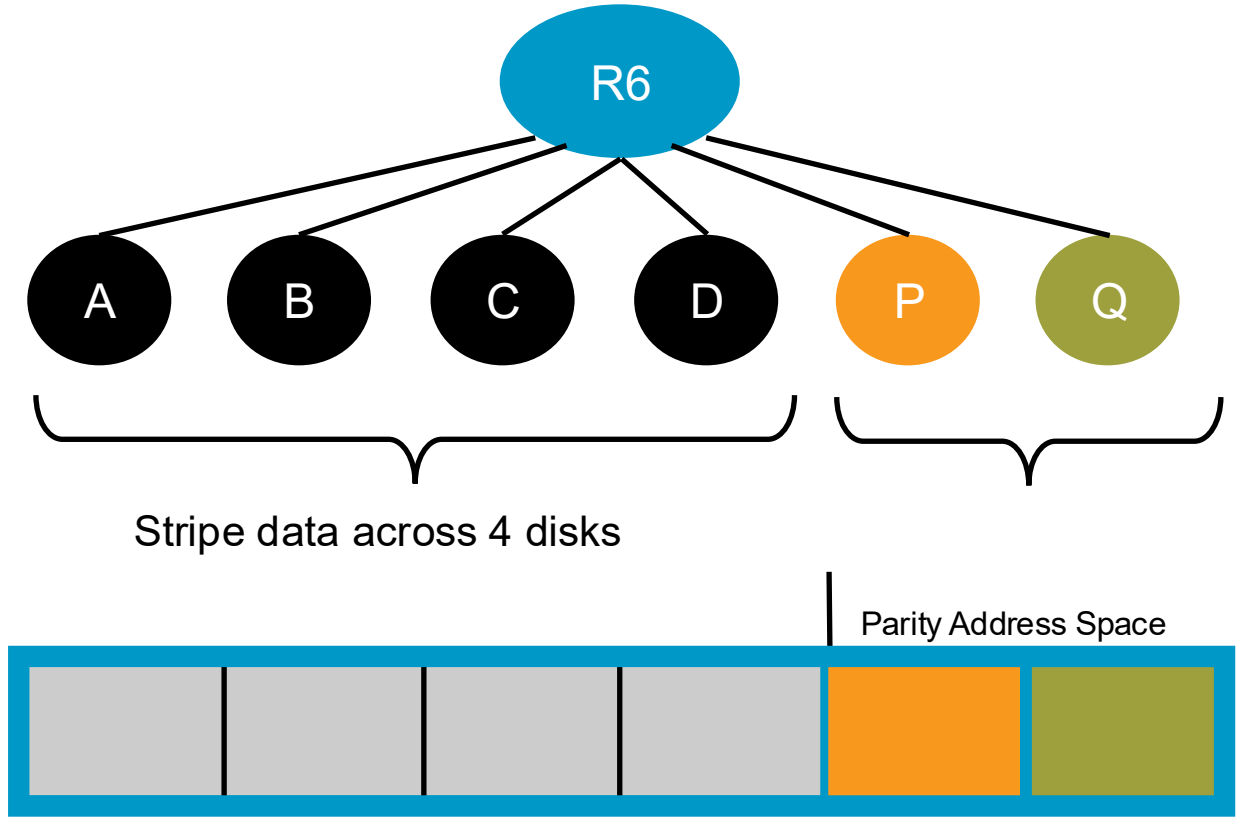
How to Improve Small Writes?

- Large writes are full stripe writes
- Small writes require partial stripe writes
- Customer workloads have small writes
- **Question**: how to improve small write performance?
- Hint: how to turn partial stripe writes to full stripe writes?



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vSAN ESA (Express Storage Architecture)

Logs to the rescue

What can aggregate writes into big chunks?

Log-structured File System (LFS):

- Always writes to new location
- Garbage collect later

Key idea: add LFS on top of vSAN OSA

Benefits of Log-Structured Write

- Full-stripe write to RAID-5/6
- Snapshot
- Compression
- QLC (large writes)
- Reduce file system metadata size
- Save CPU on encryption & compression
- Reuse vSAN OSA

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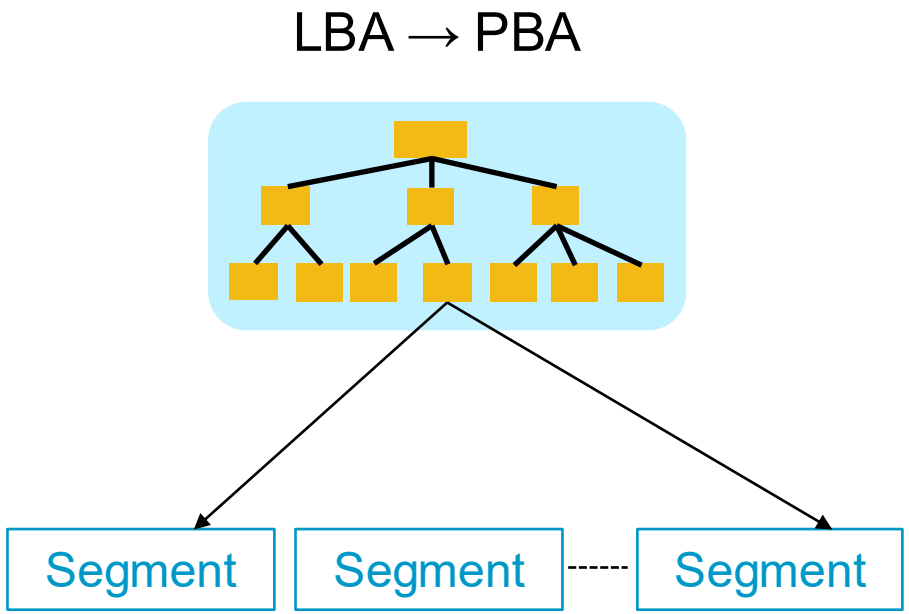
Log-structured File System

- Only need one file for a virtual block device
- One metadata map (B+ Tree) LBA → PBA
- When writing data
  - Write to new address
  - Update LBA to point to new PBA
- **Question**: how to update B+ Tree?
- Need another level of indirection
  - Virtual Address Table (VAT)
  - Store VAT in checkpoint, load on bootstrap
- Problems:
  - VAT doesn't fit in memory
  - Complicated (too many levels of indirections)
- Solution: hybrid LFS



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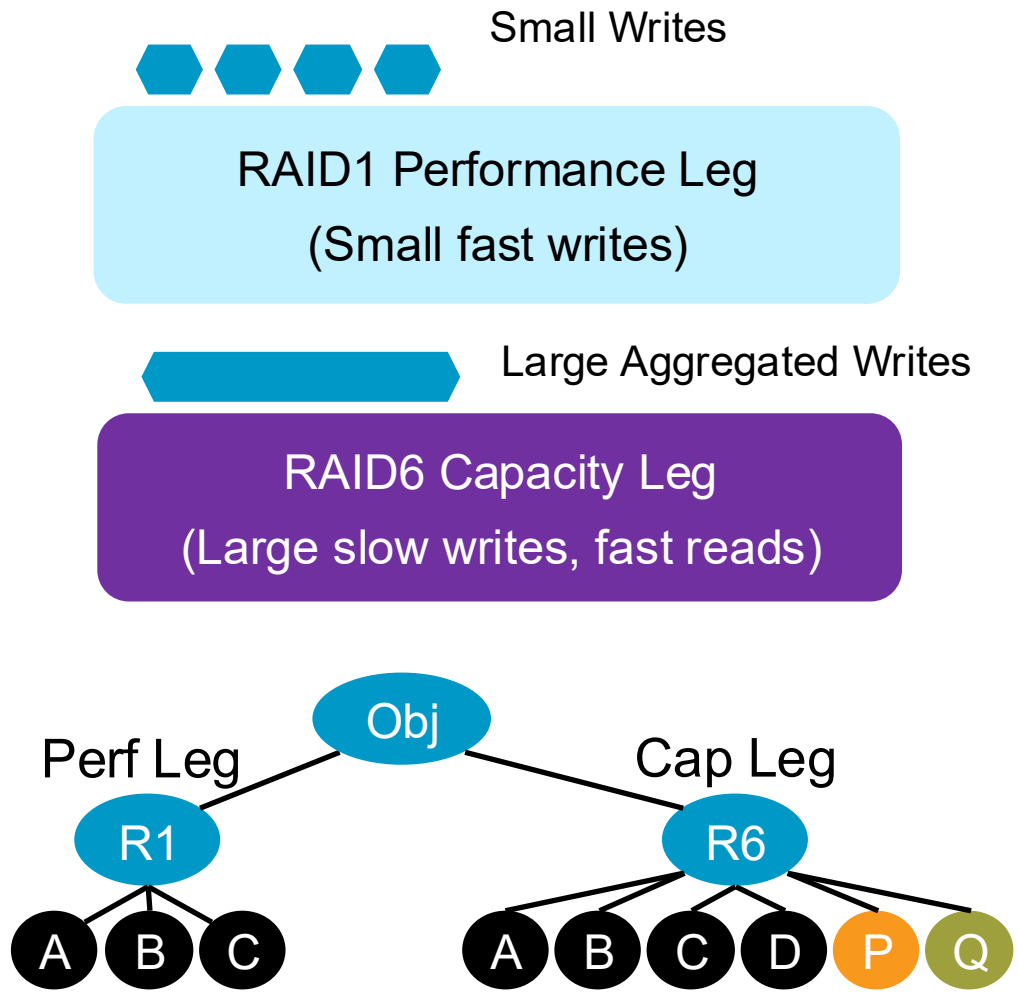
Hybrid Log-structured File System

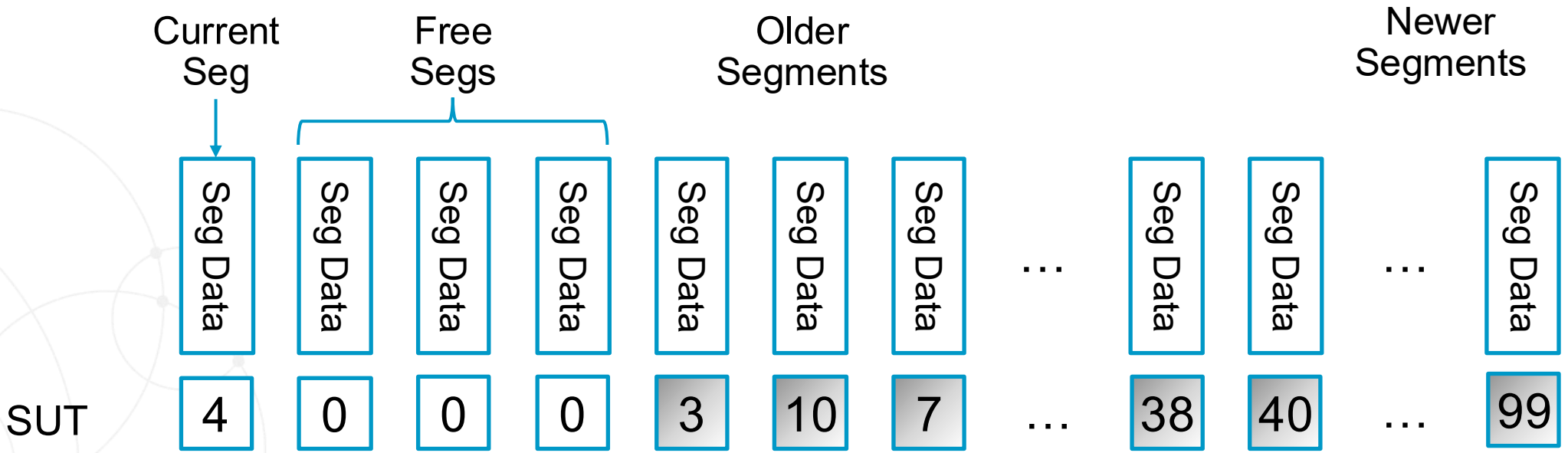
Leverage Two vSAN Policies

- Each LFS has:
  - Performance log: RAID-1 3-way mirror
    - Small writes don't cause read-modify-write
    - Stores Write-Ahead Log, B-tree pages, other metadata
  - Capacity leg: 4 + 2 RAID-6
    - Only large writes are fast
- Write small, then write big
  - Log data and metadata to aggregate
  - Data are written **twice**, but still much faster
- **Question**: why does the performance leg use a 3-way mirror, instead of a 2-way mirror?
- Both legs must tolerate 2 node failures



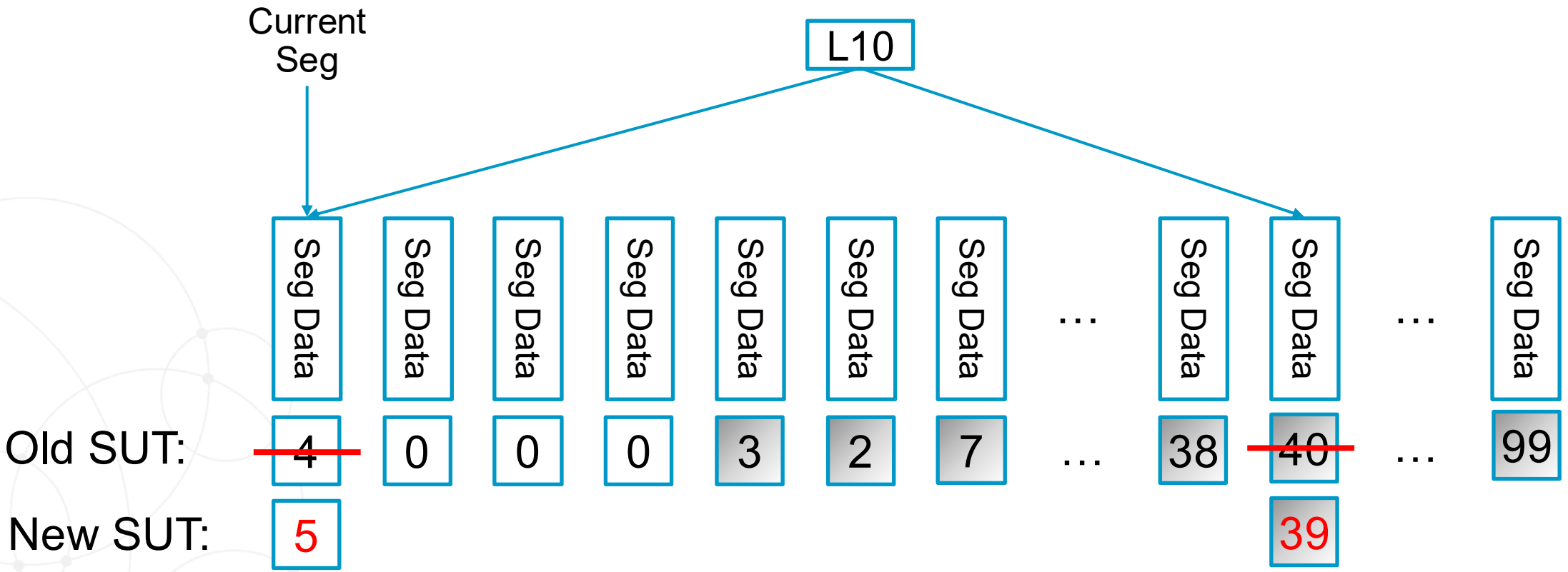
Segments and Segment Usage Table

- Free space in segments are managed by an on-disk array called “Segment Usage Table”
- Each entry in the table has:
  - numLive: number of data blocks still live



Segment Usage Table Updates

Write to Logical 10



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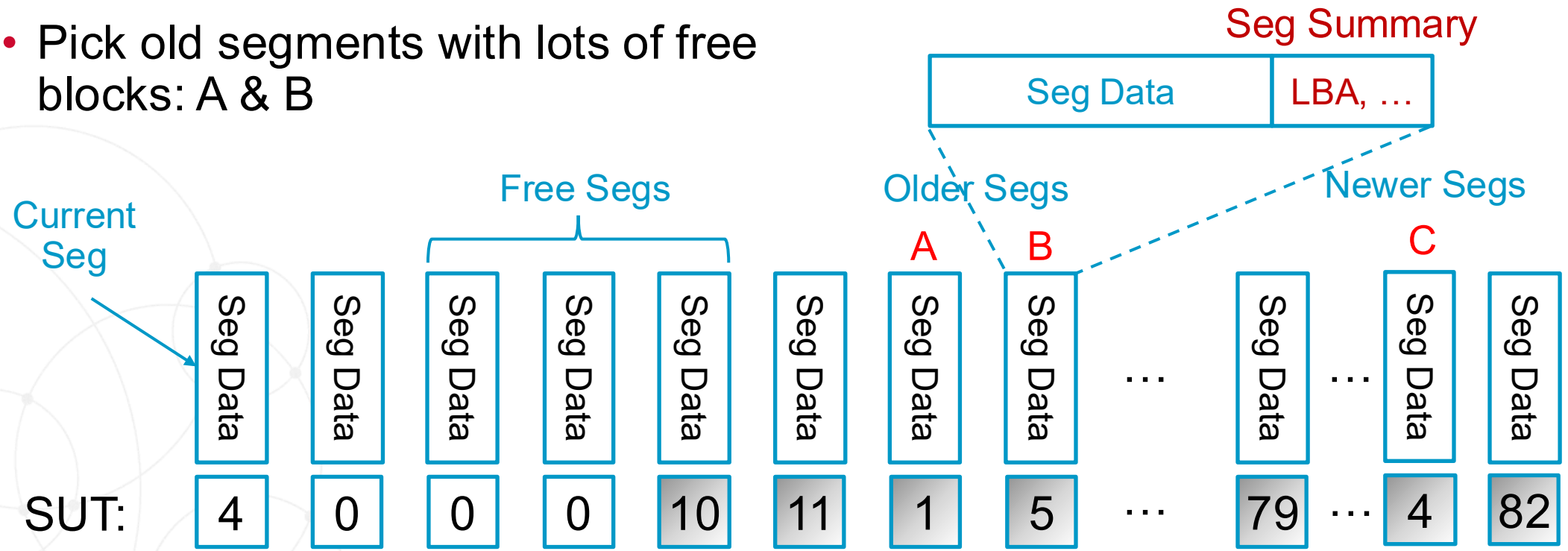
Segment Cleaning (Garbage Collection)

- Check Segment Usage Table, find best segments to clean:
- **Question**: Which 2 should be cleaned: A, B, C?
- Pick old segments with lots of free blocks: A & B

- How to clean a segment:
  - Read a segment
  - Use "Segment Summary" to find live blocks
  - Write live blocks to new location



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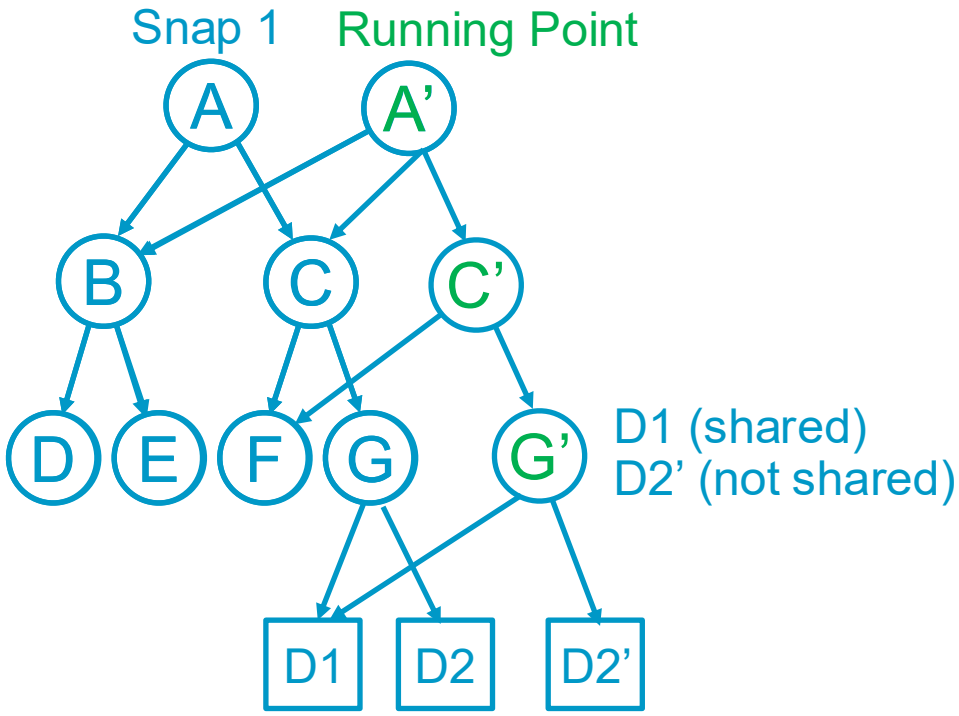
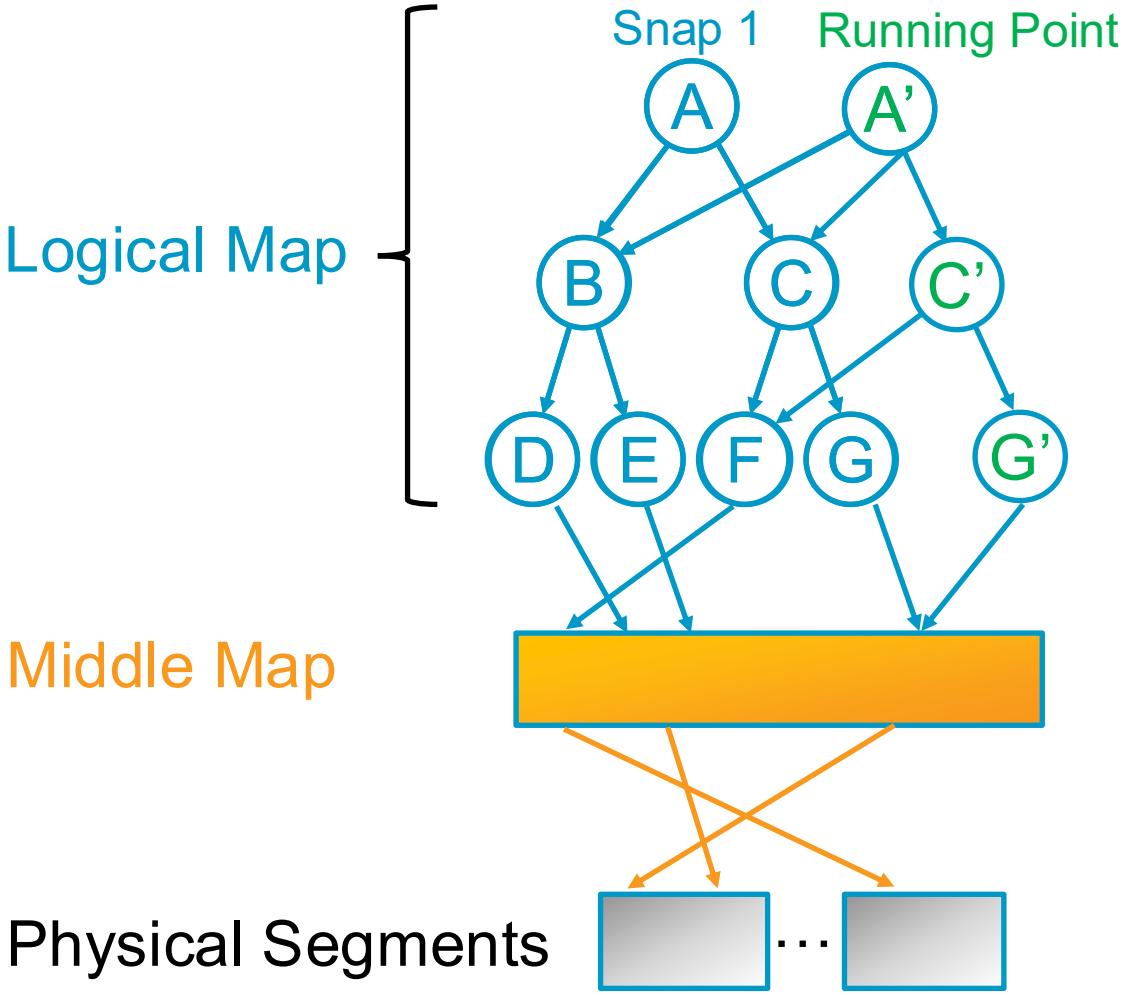
Snapshot Design – Snapshots and Clones

- Snapshot: keep old data & copy metadata
  - Keep old data: solved by LFS
  - Copy metadata: Copy-On-Write B-tree
- Snapshot creation
  - Clone a B-tree
- Snapshot deletion
  - Compare the previous and next B-trees to identify shared pages
- **Question**: How many LBAs point to a PBA and how does segment cleaner move blocks?
- **Question**: how to limit metadata updates during block moving?



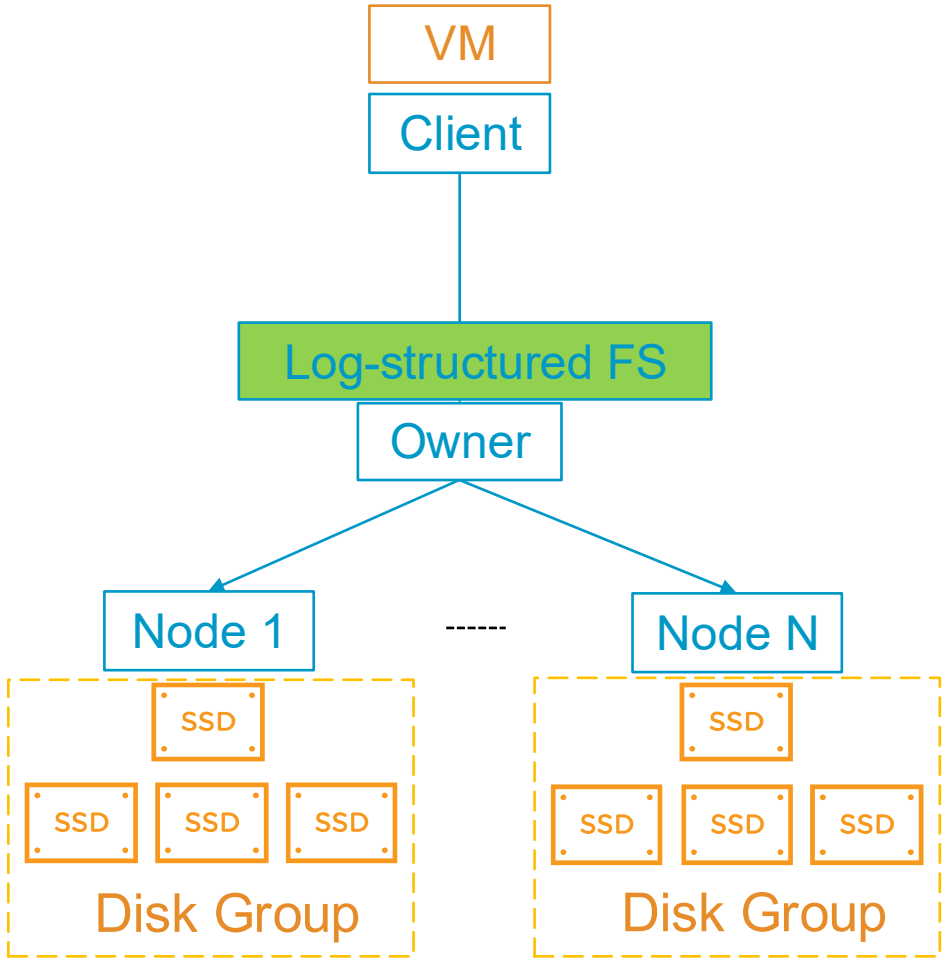
Snapshot Design – COW B-tree with Middle Map

- Logical Map B-tree
  - Key: LBA (Logical Block Address)
  - Val: MBA (Middle Block Address), NumBlocks
  - Example: L0 → M10, N20
  - LBA → MBA is N:1
- Middle Map B-tree
  - Key: MBA
  - Val: PBA (Physical Block Address), NumBlocks
  - Example: M10 → P100, N2
  - MBA → PBA is 1:1
- **Question**: now how does segment cleaner move a block?



vSAN ESA Complete Data Path

- New Log-structured File System
  - Full-stripe write
  - Compression
  - Snapshot
  - …
- New local file system to replace old disk group
  - Fix bottlenecks of performance tier SSD and CPU



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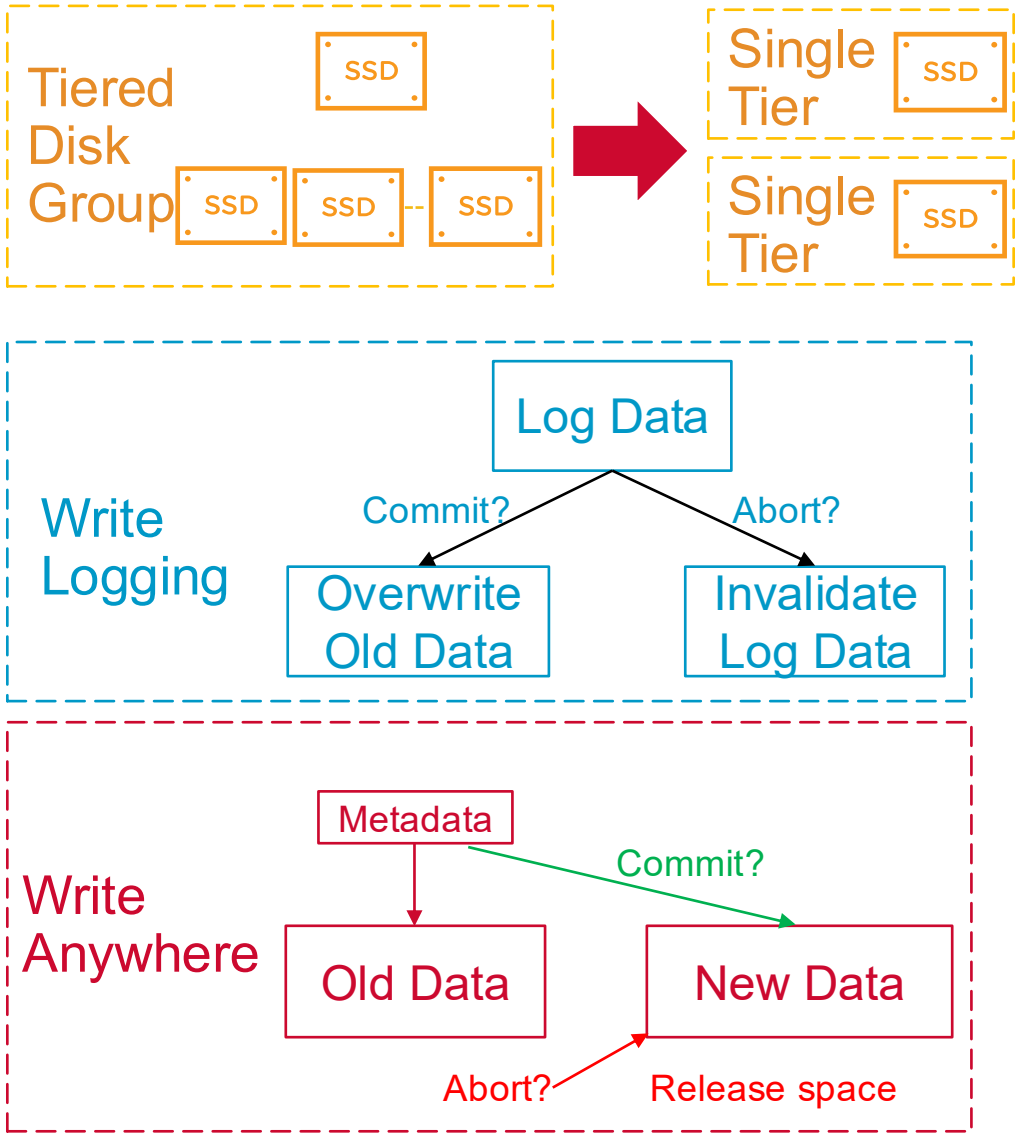
New Local File System

- Remove “Disk Group” concept
- Single Tier design – each SSD is an independent file system
- **Question**: How to implement 2PC, Write Logging, or Write Anywhere?
- Write Anywhere avoids double write



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vSAN ESA Execution and Performance Results

- Large team effort to discuss, design, and implement
- Performance tuning is an ongoing task
- Achieved much better performance
- Snapshots are > 100x faster

Workload	Throughput	CPU per IO
70/30 8k RW	5.2x	2.6x drop
8k rand read	2.6x	6% increase
Large write	3.1	1.33x drop

vSAN ESA vs. OSA
on identical hardware

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Conclusions and Q&A

- Principles of designing distributed storage systems
  - Design safe, fast system that fit the hardware
  - Some over-engineering to fit future hardware
  - Reuse existing system when possible
- vSAN OSA was designed for HDD
  - Extended its life into SSD
- vSAN ESA is designed for NVMe
  - Reused most of OSA
  - Added a log-structured file system on OSA
  - Achieved 5x performance on identical hardware

Thanks to Eric Knauft for some slides I've borrowed from him.

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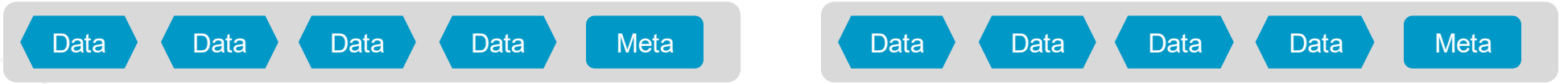
The Importance of Amortization

Adding layers of metadata can cause extra IO, led to worse performance

Offset this by amortizing the cost

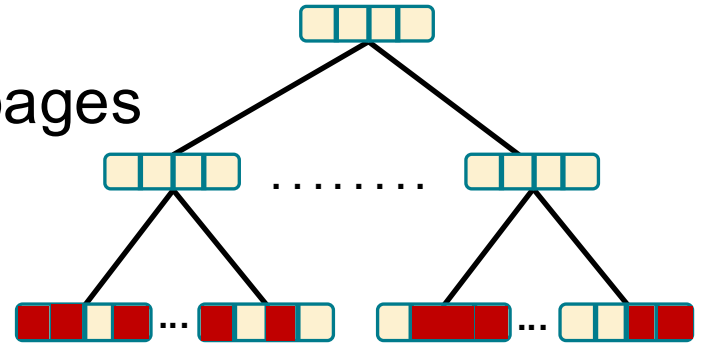
- One large IO operation is more efficient than many small IO operations

Log IOs: write all the in-flight IOs and their metadata into a single IO



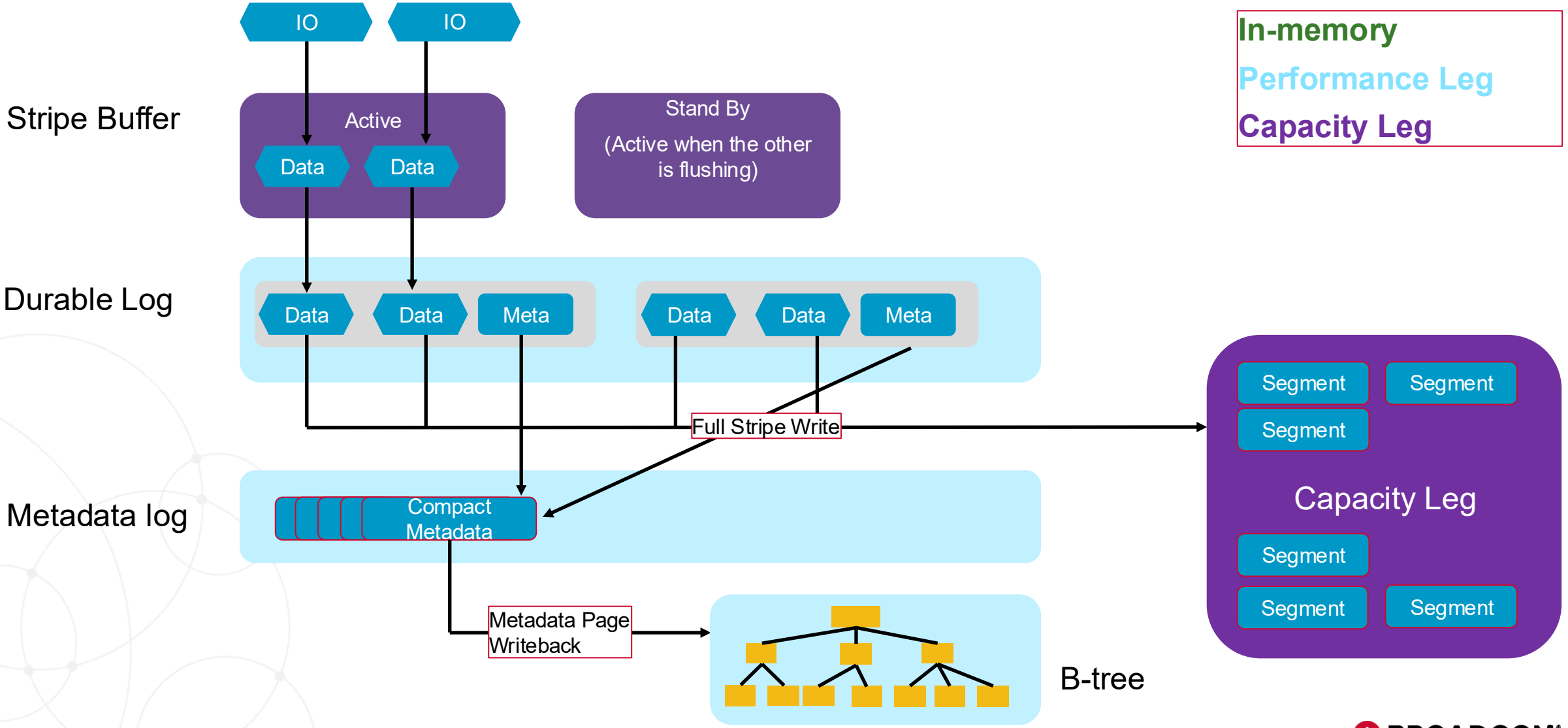
Get lots of hits in the same B-tree pages

- Requires keeping things in memory for a while



2.5 updates per page

IO Flow



Segment Cleaning with Segment Summary

- Segment summary has the LBAs of every block in the segment
- Assume segment size is 100 blocks
- PBA of segment 1 is P100 – P199
- Segment summary of segment 1: L80, L90
- Current logical map values:
  - L80 ➔ P530
  - L90 ➔ P120
- Which block is live?

Cleaning Procedure:

- Read segment 1
- Find out L90 is live
- Write L90 to new segment 3 with PBA 300
- Update logical map: L90 ➔ P300

