STORAGE DEVELOPER CONFERENCE
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Kinetic Campaign

Speeding Up Scientific Data Analytics with Computational Storage Drives and Multi-Level Erasure Coding

Qing Zheng

Scientist, Los Alamos National Laboratory (LANL)

LA-UR-22-29500

About Me

- HPC Storage Scientist at Los Alamos National Laboratory
- I received my PhD at Carnegie Mellon University in 2021
- I do distributed filesystem metadata management, KV stores, scientific data analytics
- https://zhengqmark.github.io

Agenda

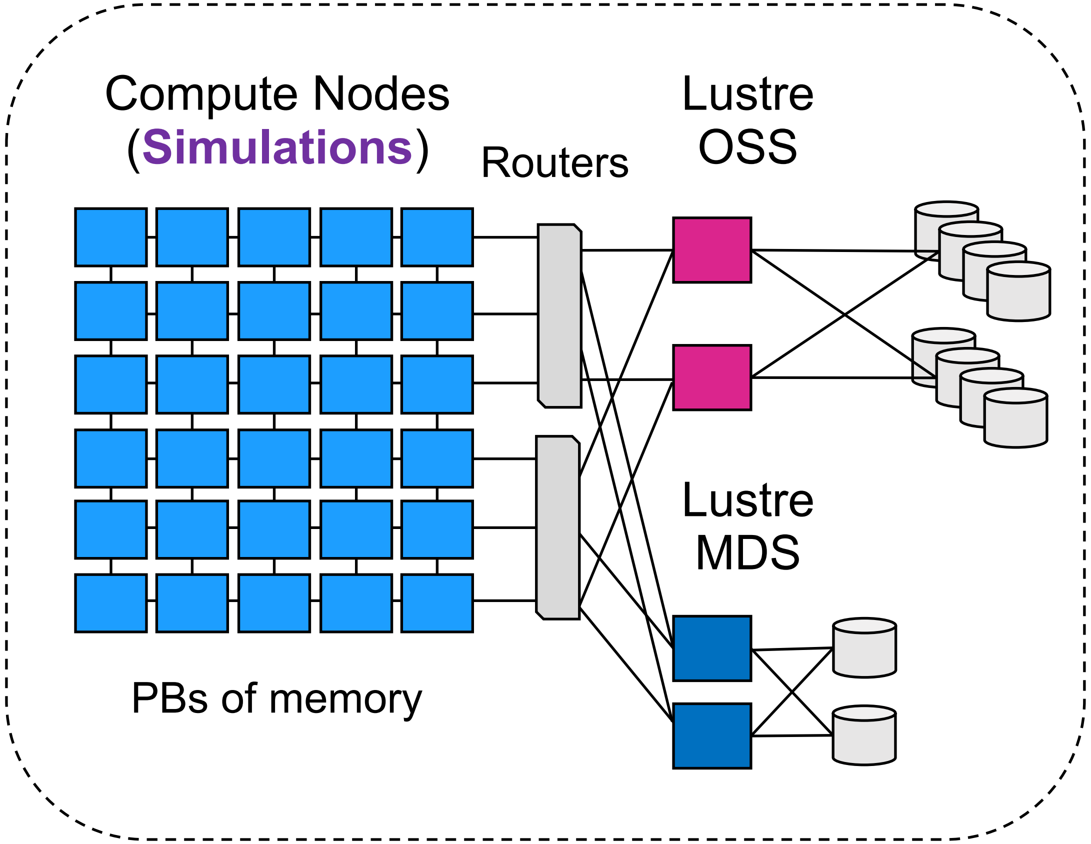
- Why computational storage: large-scale data analytics challenges in HPC
- MarFS: LANL's current archival storage using erasure coding
- Kinetic: Seagate's novel active disk research platform
- C2: LANL's next-gen archival storage combing in-drive computing and erasure coding for cost-effective data protection, storage, and rapid queries

Large-Scale Data Analytics Challenges in HPC

Why computational storage?

Typical HPC Simulation Workflow at LANL

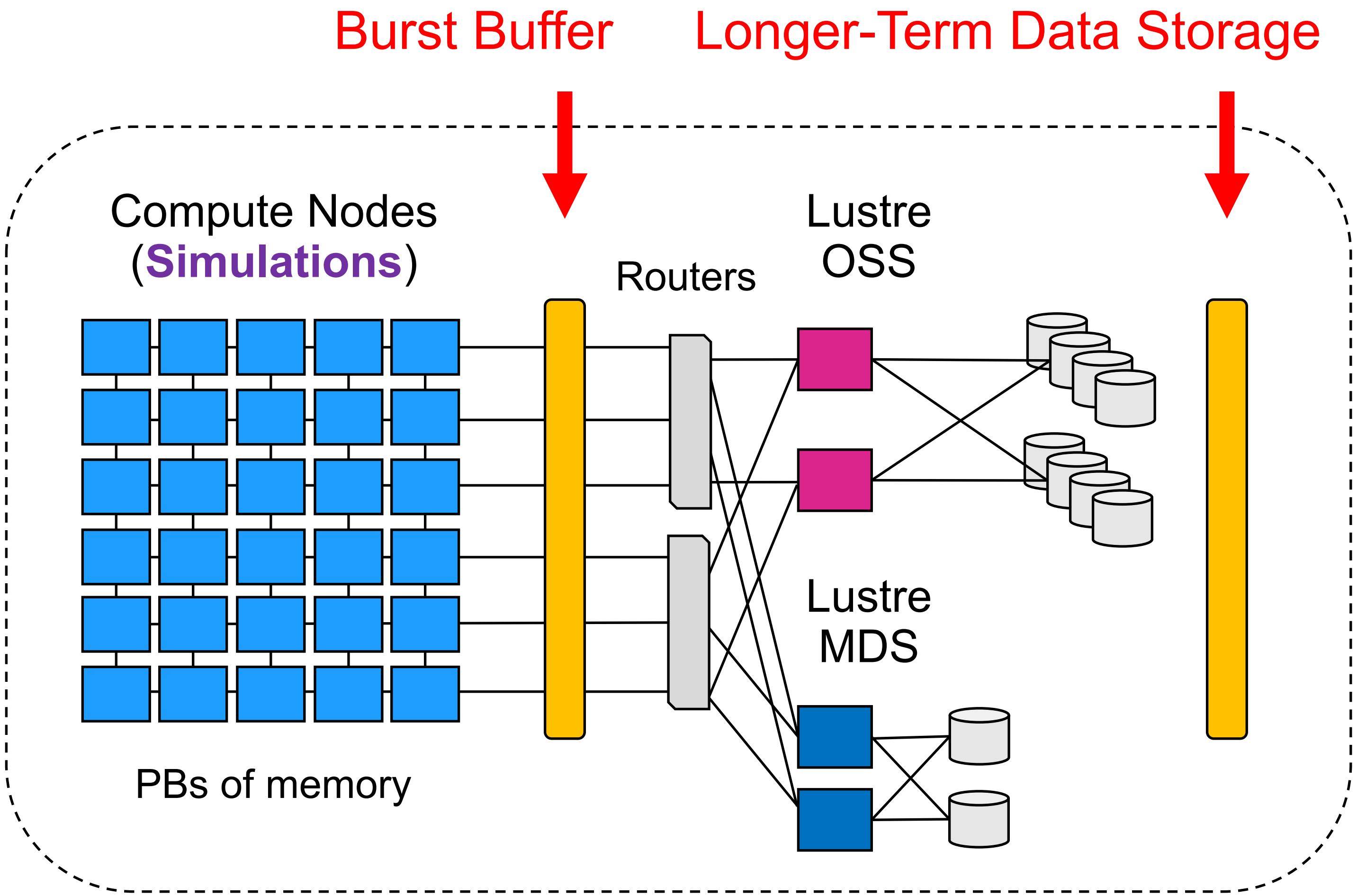
- Simulation writes state to storage periodically
- Analysis code later reads data back for in-mem operations (e.g.: movie making)
- Data may not compress
- Performance depends on available storage bandwidth



A modern HPC platform

Trend #1: Multi-Tiering for Cost-Effective High Bandwidth

- Tackling larger data requires higher bandwidth
- No single media type can provide both speed & capacity at the same time (given a cost budget)
- Result: storage increasingly tiered

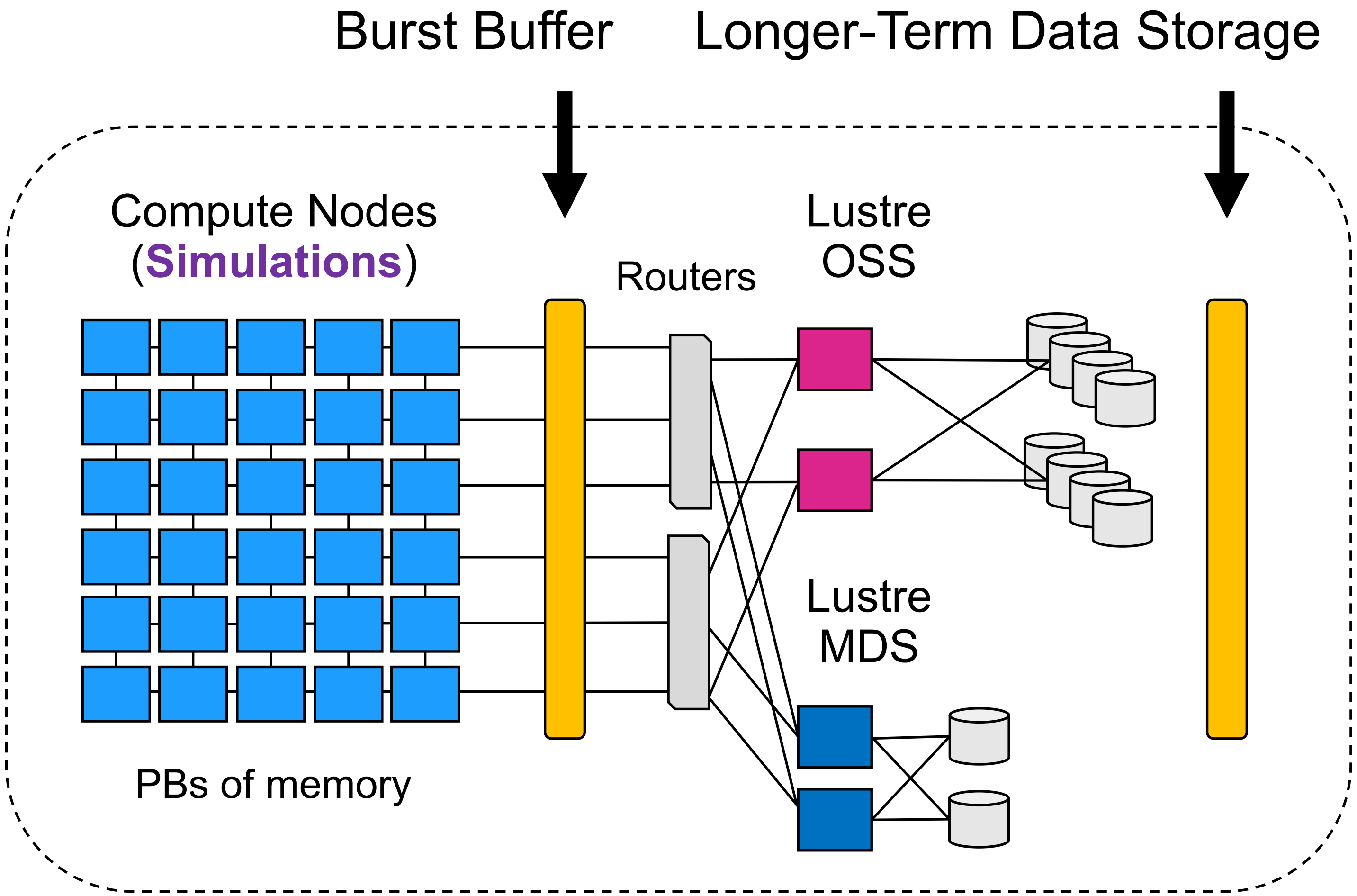


A more recent HPC platform

Challenge #1: Asymmetric Read-Write Performance

- Writing data to storage may continue to be fast thanks to multi-tiering

- Reading data from storage can be much slower (when data is streamed from the slow tiers)



A more recent HPC platform

Trend #2: Analysis Increasingly Selective

- Analysis used to read back an entire dataset
- Today: queries tend to only target a small subset of data
- Need to avoid excessive data reads (especially when reading from a slow storage media)

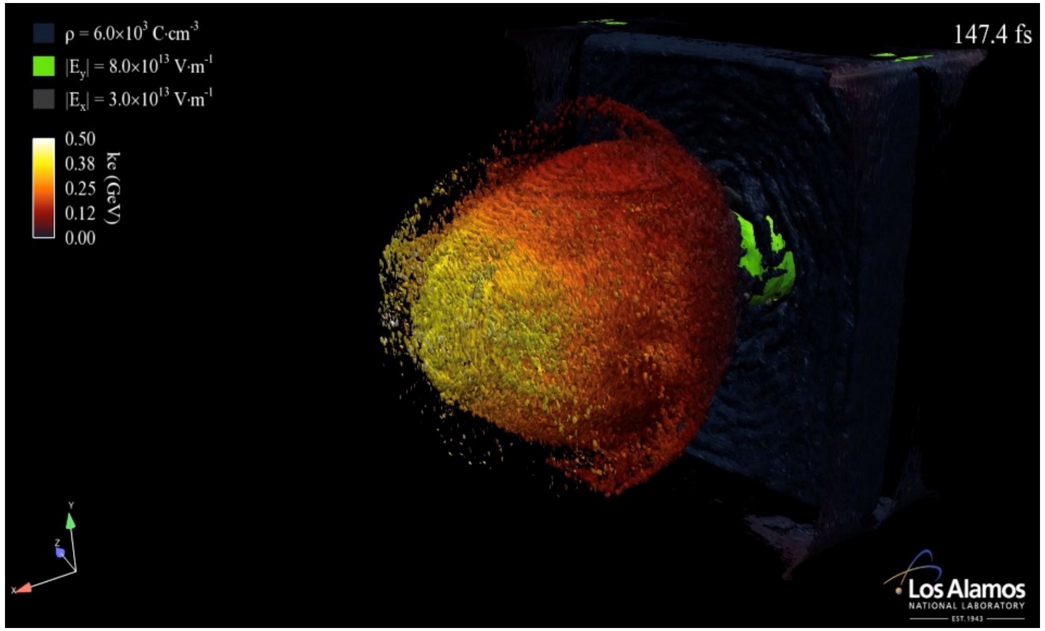


Image from LANL VPIC simulation done by L. Yin, et al at SC10. X, Y, Z are 3D locations of a particle. Ke is a particle's energy.

Example: SELECT X, Y, Z FROM particles **WHERE** Ke >= 1.5

Less than **0.1% or 0.00001%** needs to be read from storage

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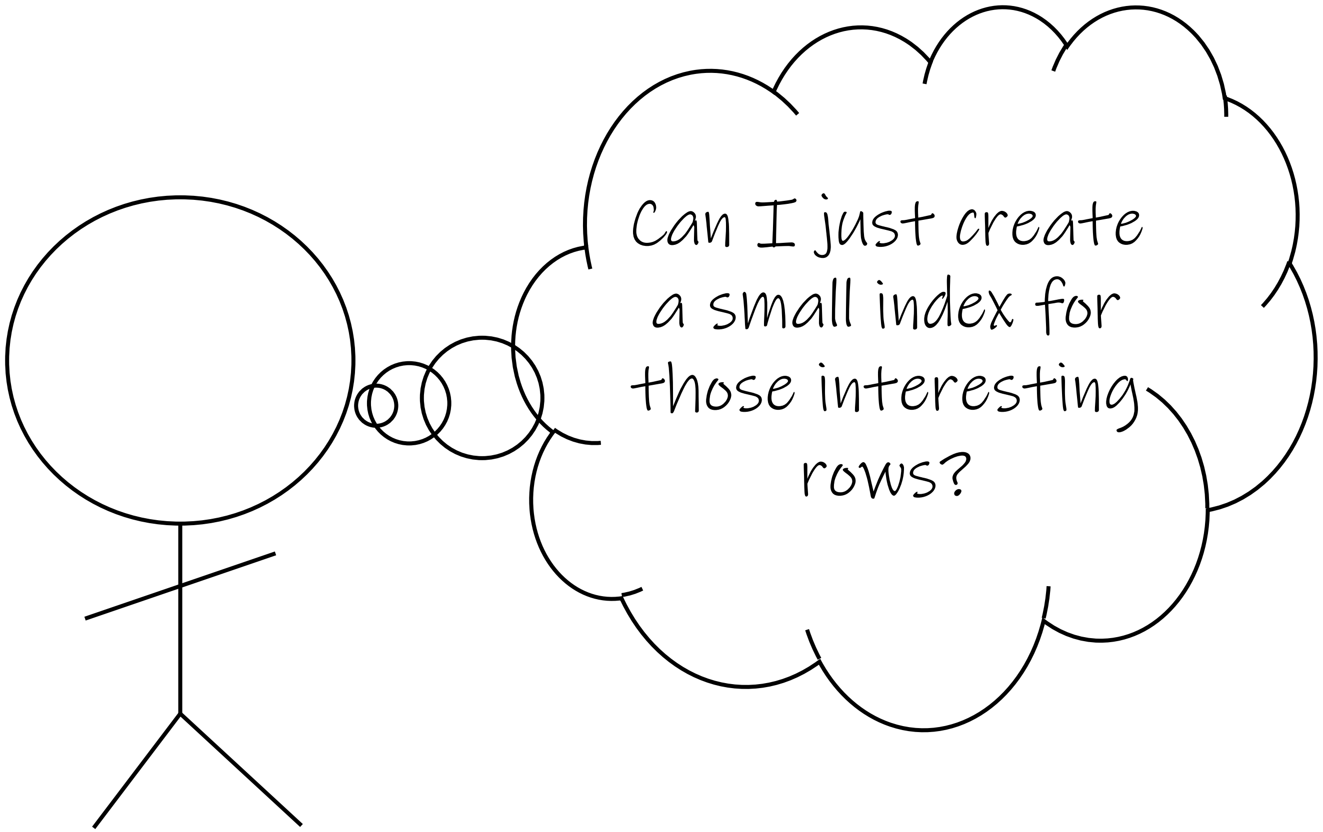
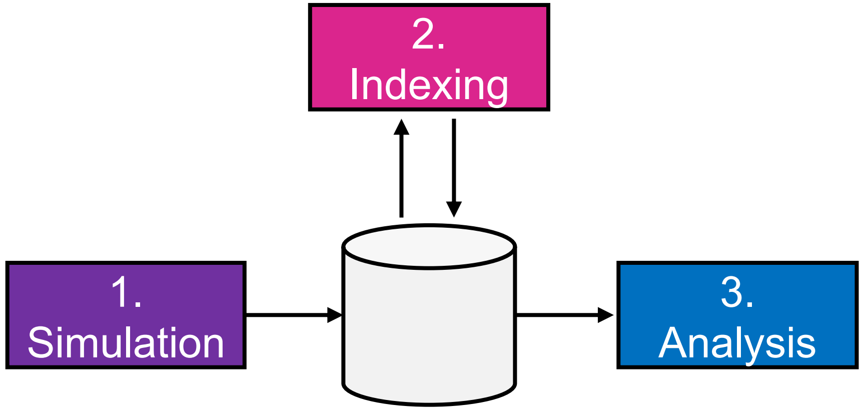
Challenge #2: How to Read Back Just Interesting Rows

- Data known to be interesting only at simulation end
- Indexing only works when all rows are indexed at all simulation timesteps
- Compute node resources are limited
- Sorting only helps 1 query



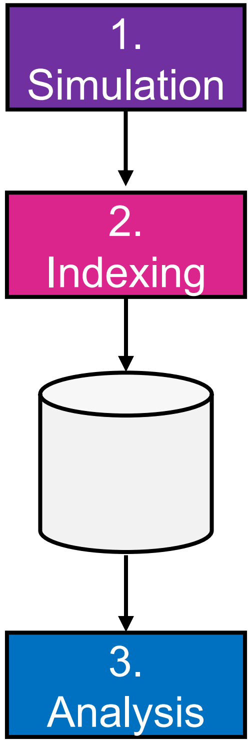
Existing Solutions Fall Short in Different Ways

Post-processing



Excessive data movement

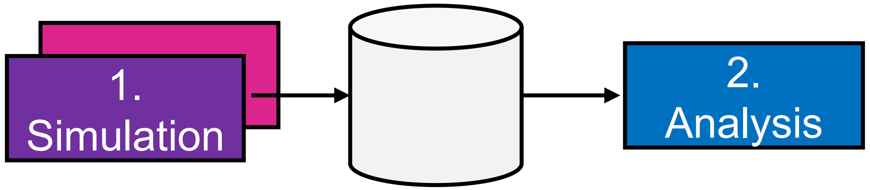
In-transit processing



Requires additional compute nodes than the job

Does not work for large jobs

In-situ processing

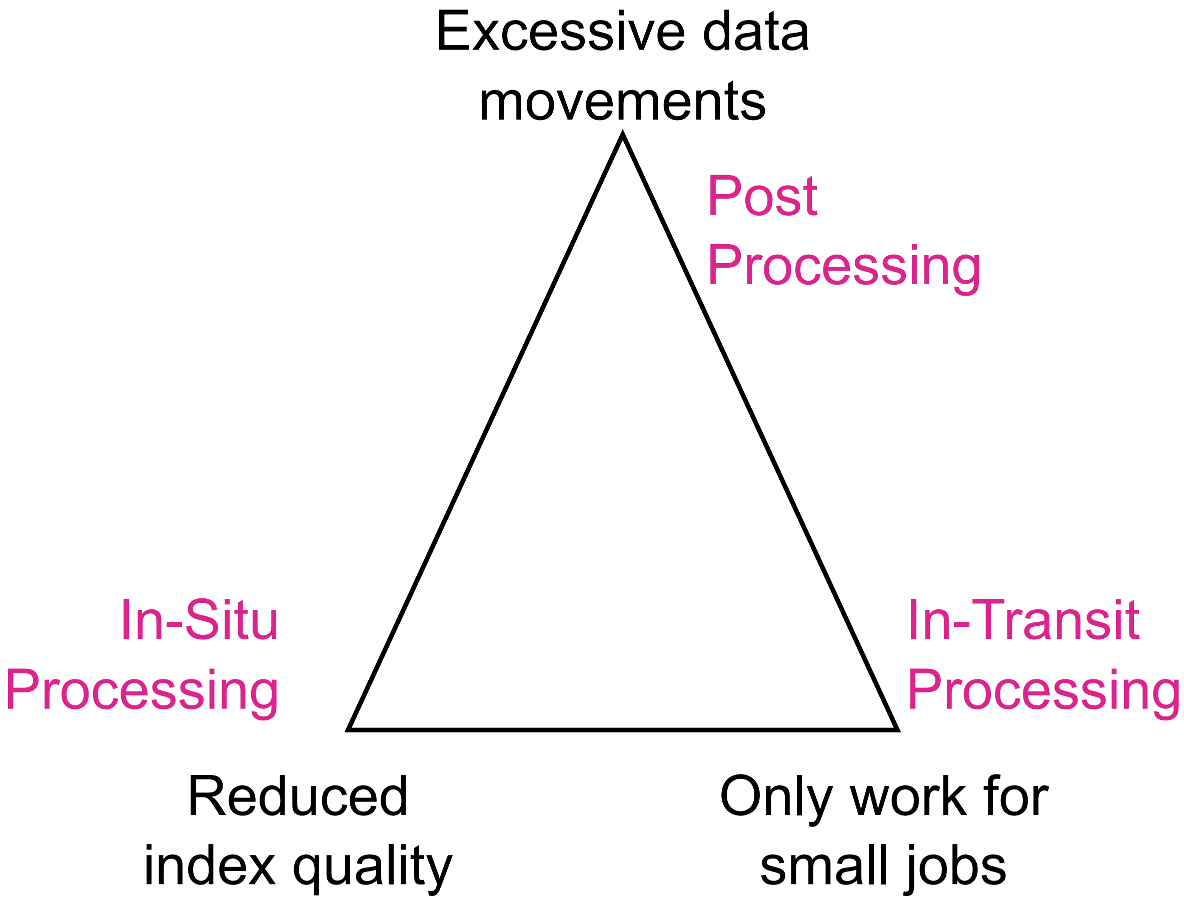


Can only index a single column

Does not work for multi-dimensional queries

Opportunities for Rapid Query Acceleration

- Today: all computation takes place on compute nodes
- Excessive data movements or reduced index quality or increased per-job resource footprint
- Computational storage allows for overcoming existing solution limitations (by offloading compute to storage reducing data movement)



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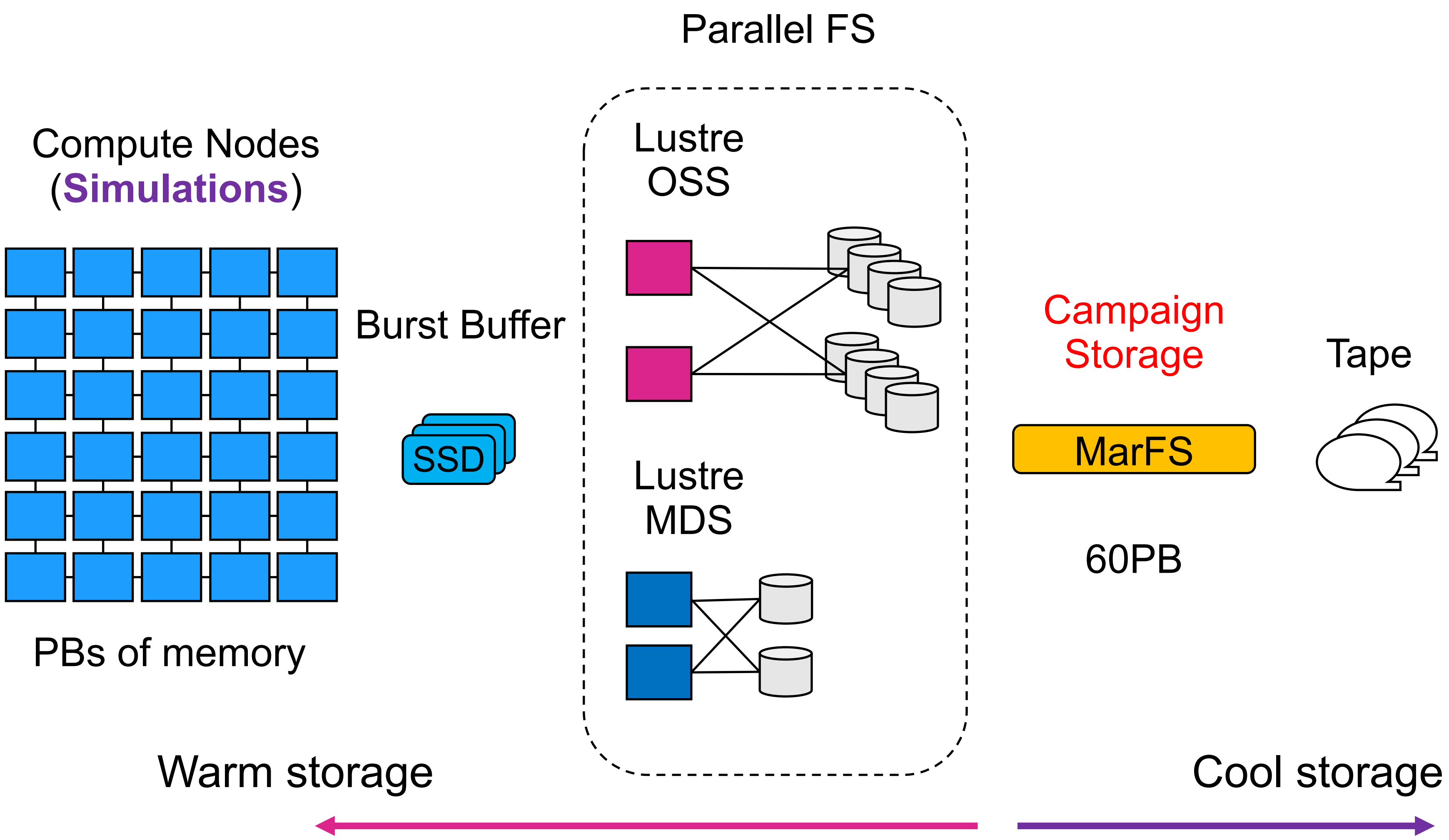
MarFS: LANL's Current Cool Storage Tier

Multi-level erasure coding

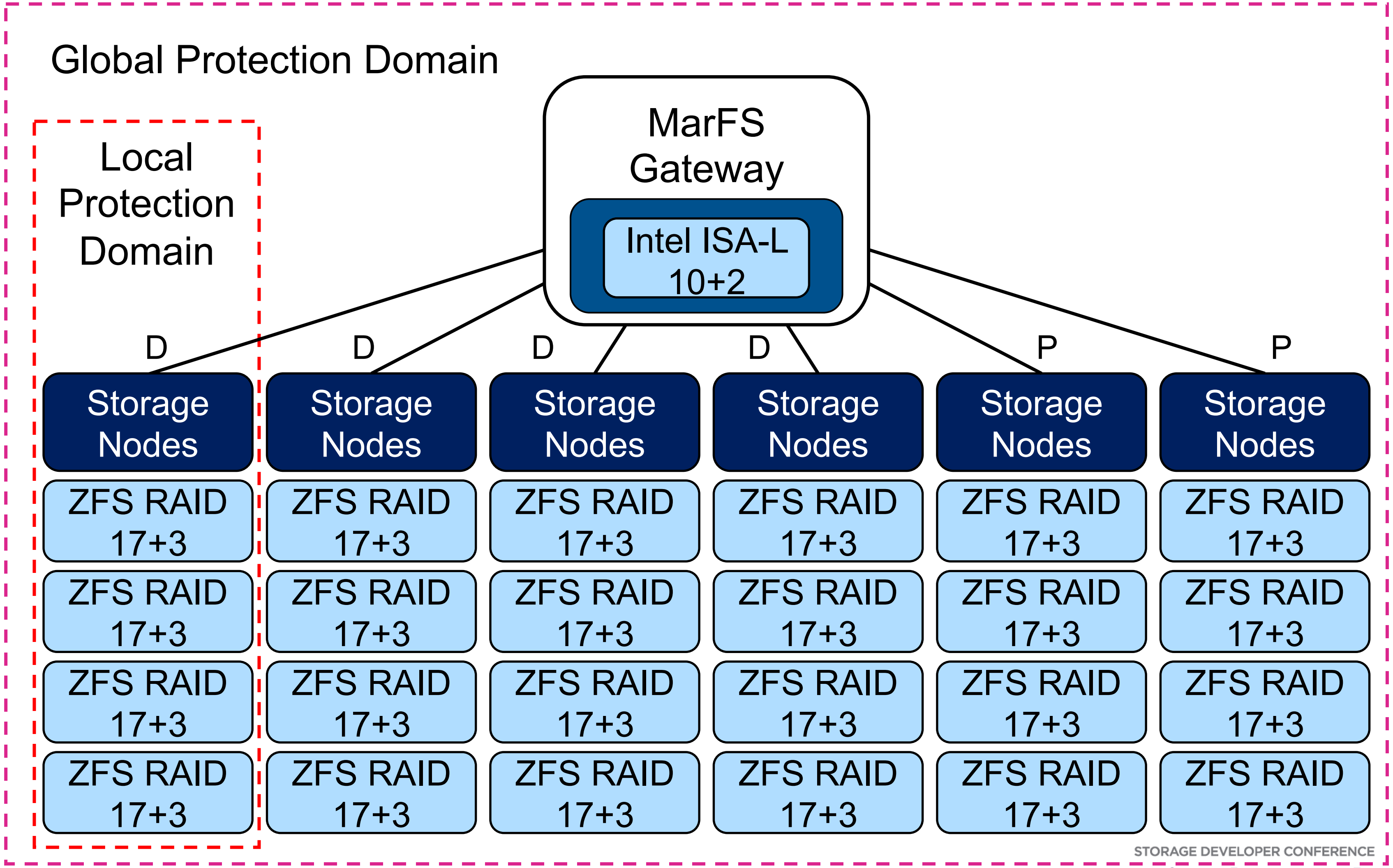
Overview of LANL's Multi-Tier Storage Infrastructure

- Burst buffer
  - 3.2TB/s
- Parallel FS
  - 1.2TB/s
- Campaign storage
  - 50-100GB/s
- Tape
  - 10GB/s

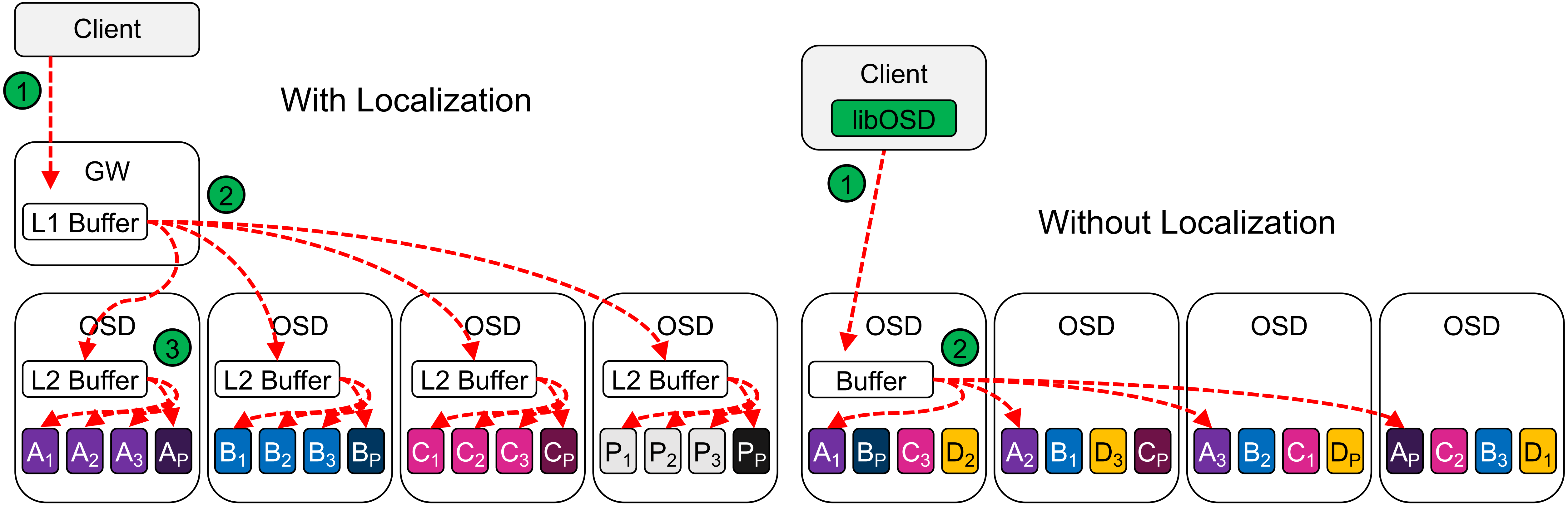


Multi-Level Erasure Coding in MarFS

- Layered data protection domains for localized repair
- Data & parity round-robined to storage nodes
- Multiple JBODs per storage node using SMR drives



Cost-Effective Data Protection Through Localization



Most rebuilds are done within a single OSD **without being limited by inter-OSD bandwidth**

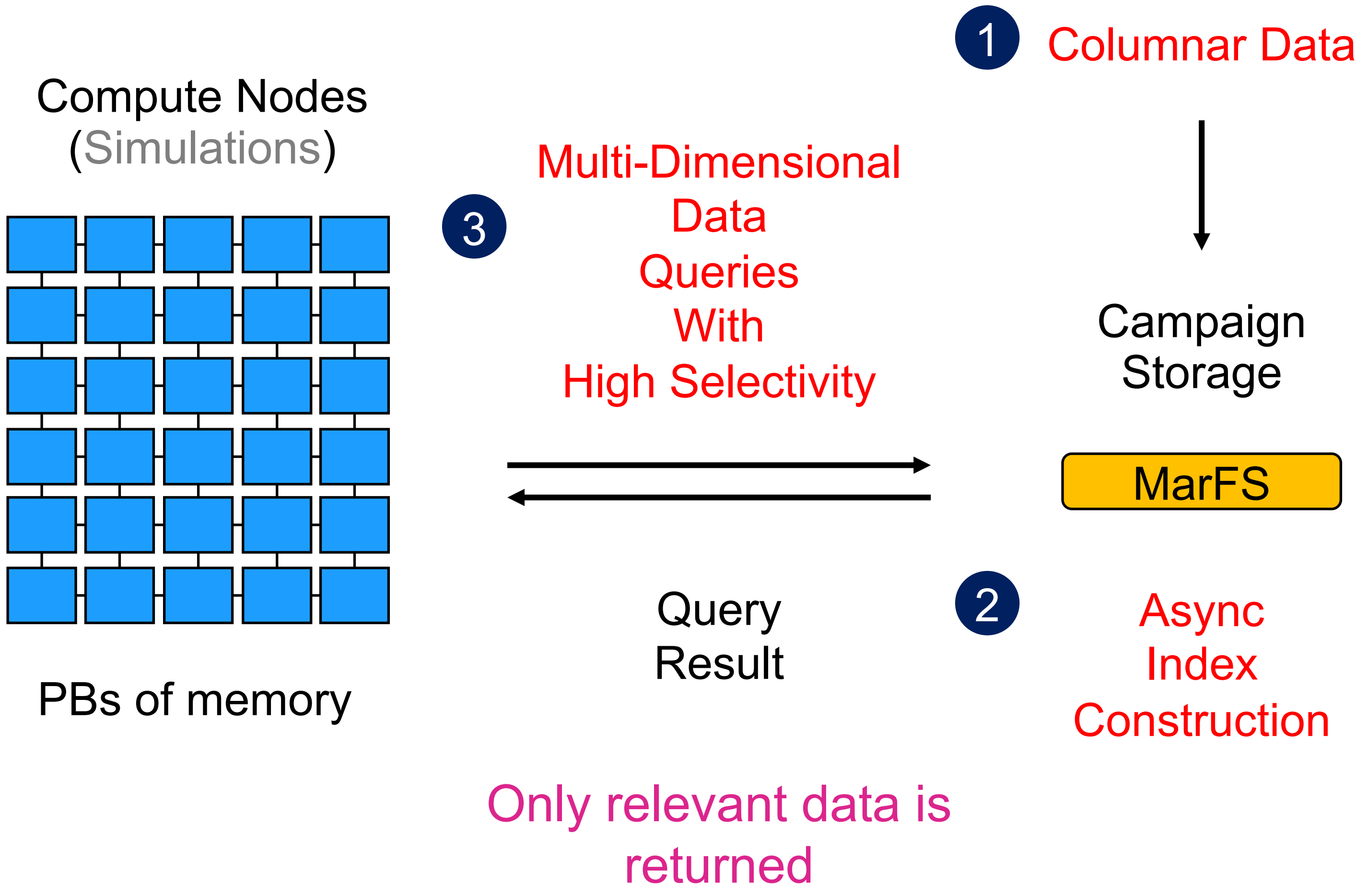
Performance depends on having a high inter-OSD bandwidth

Increased storage overhead for parity

Lower parity overhead

Towards a Computational Campaign Storage Tier

- Upper layer writes data in a columnar format with lightweight indexes (min, max) every MBs of data
- Campaign constructs detailed row-level indexes offline
- Queries run on storage incurring minimal data movement



Kinetic: A Seagate's Research Active Disk Platform

CS-HDD for in-drive computation

Computational Storage for High-Density Disk Drives

- Kinetic HDD = Disk + an envoy card
- Envoy:
  - CPU: 2x ARM Cortex-A53 cores
  - RAM: 1GB
  - OS: Ubuntu 20.04.4 (Linux 5.16.17)
  - Network: 2x Ethernet ports
    - 2.5Gb/s per port
- Ethernet uses the standard SAS connector interface with repurposed pin outs

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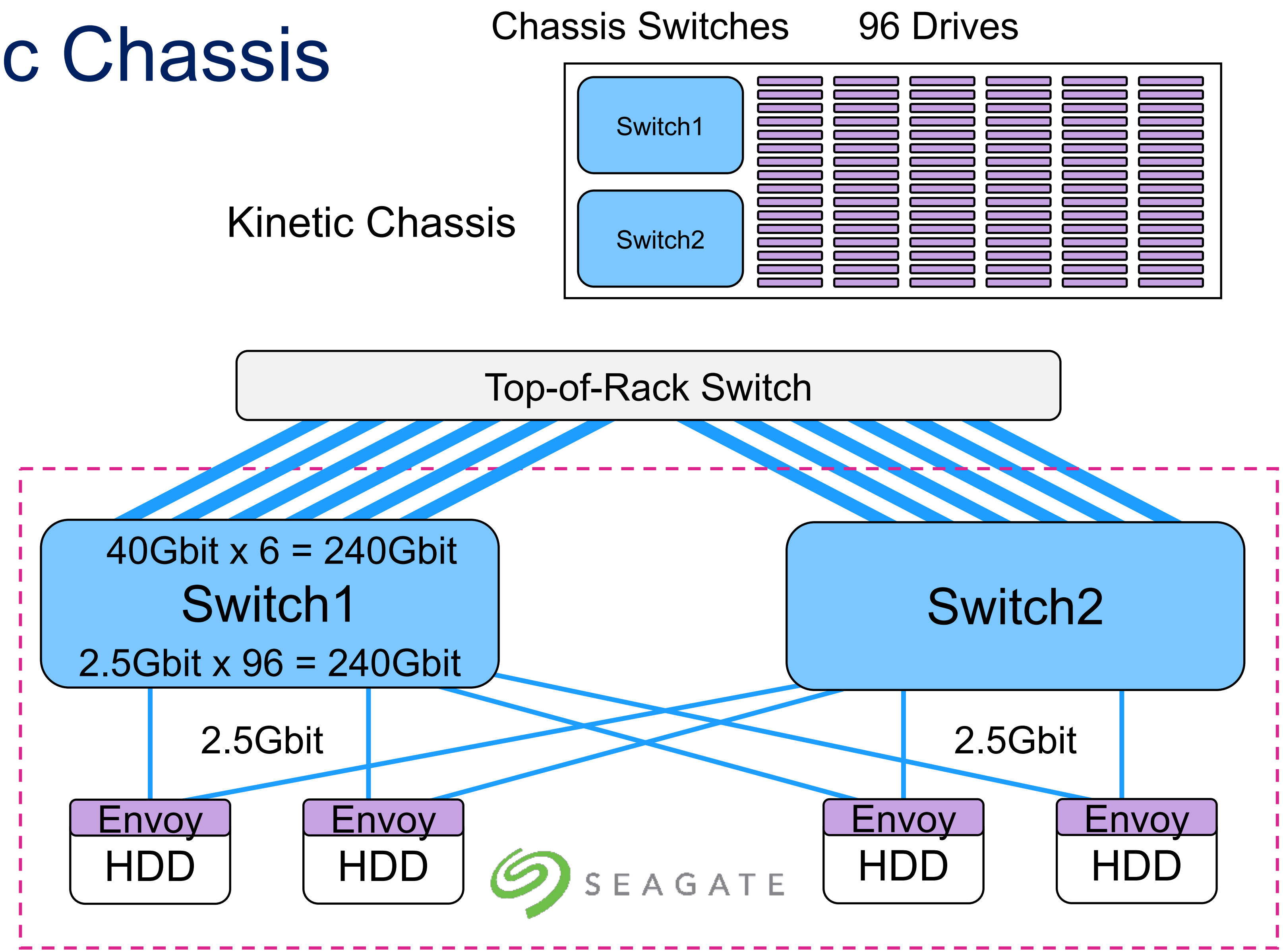
96 Drives Per Kinetic Chassis

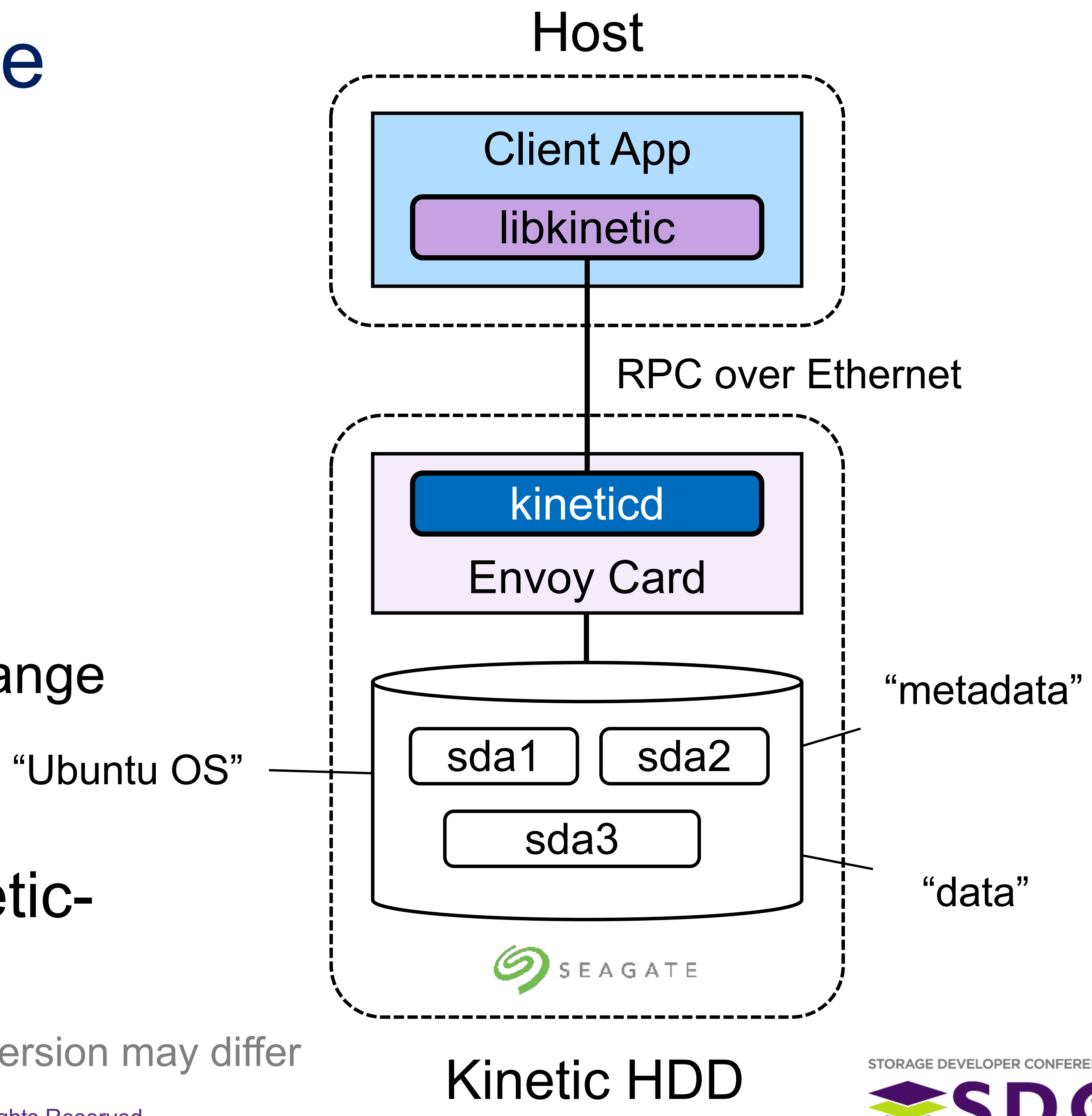
- Total capacity: 1.5PB (96 x 16TB)
- Each drive has an IP (acts like a server)
- Total bandwidth: 240Gb/s (96 x 2.5Gb/s)
  - Fully subscribed
- HA: 2 sets of switches per chassis, 2 NIC ports per drive



Kinetic Chassis

Ordered KV Based Storage

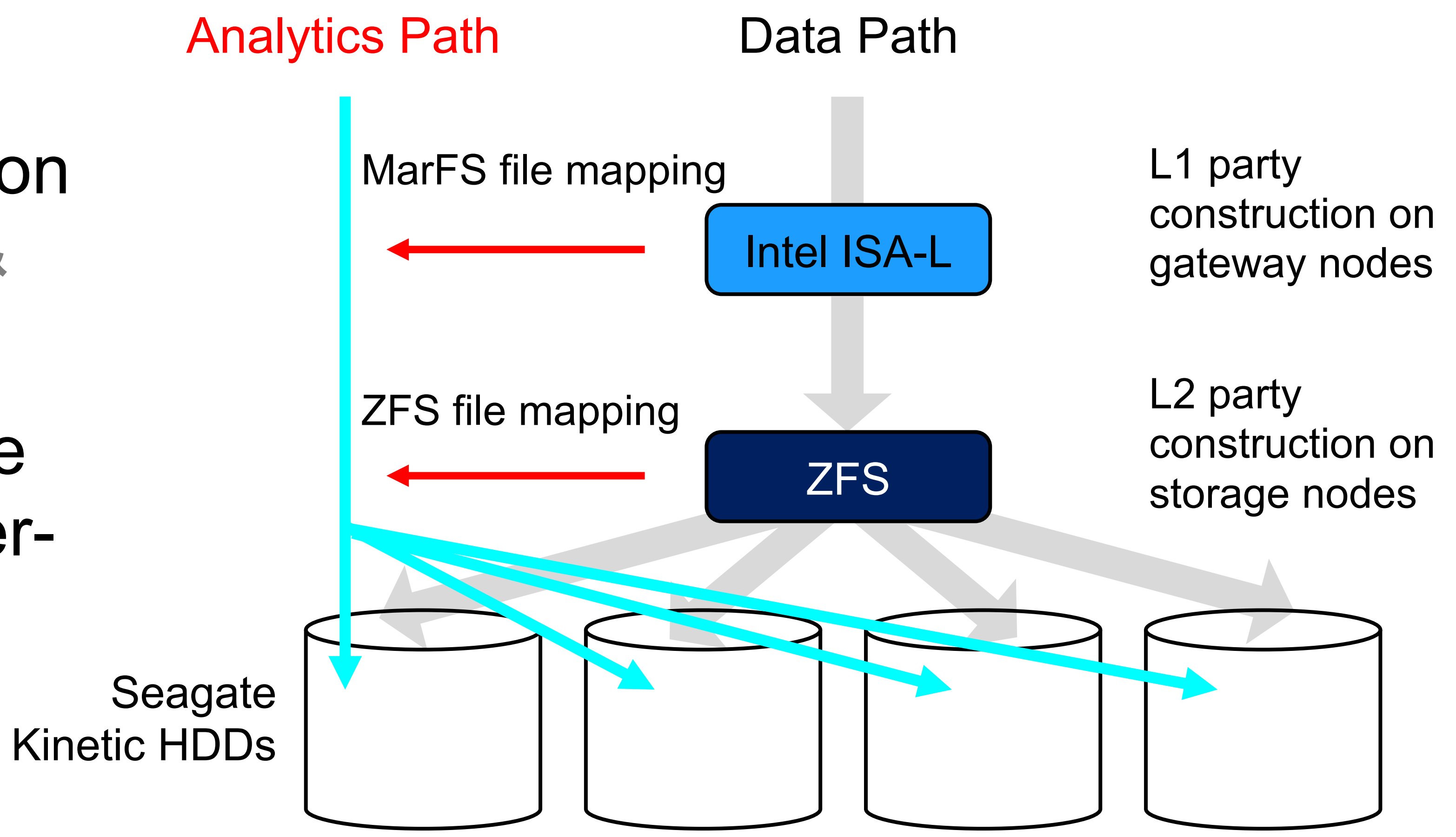
- Kinetic API
  - Ping
  - Device Erase (like mkfs)
  - Put, Get, Delete
  - Iteration: GetPrev, GetNext, GetRange
  - Exec (eBPF or C++ progs)
- More info: https://gitlab.com/kinetic-storage/libkinetic



Production version may differ

Transform MarFS to a Computational Campaign

- Kinetic HDDs for near-storage data computation (async index creation & query processing)
- Latest MarFS & ZFS file mapping for locating per-dataset disk blocks
- A shim layer that translates disk LBAs to Kinetic KVs

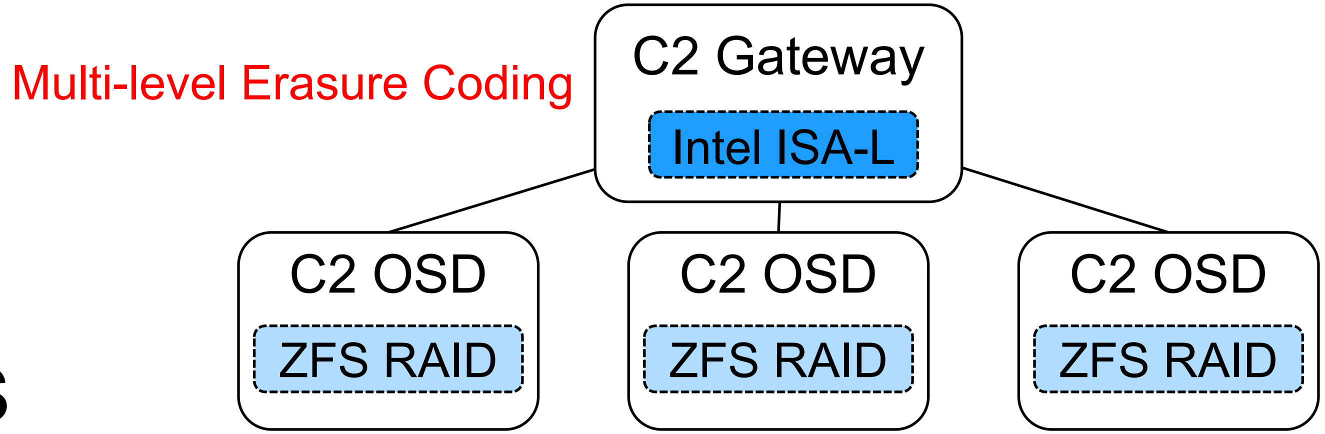


Analysis code (eBPF) stores results as new KV pairs on storage for later retrieval

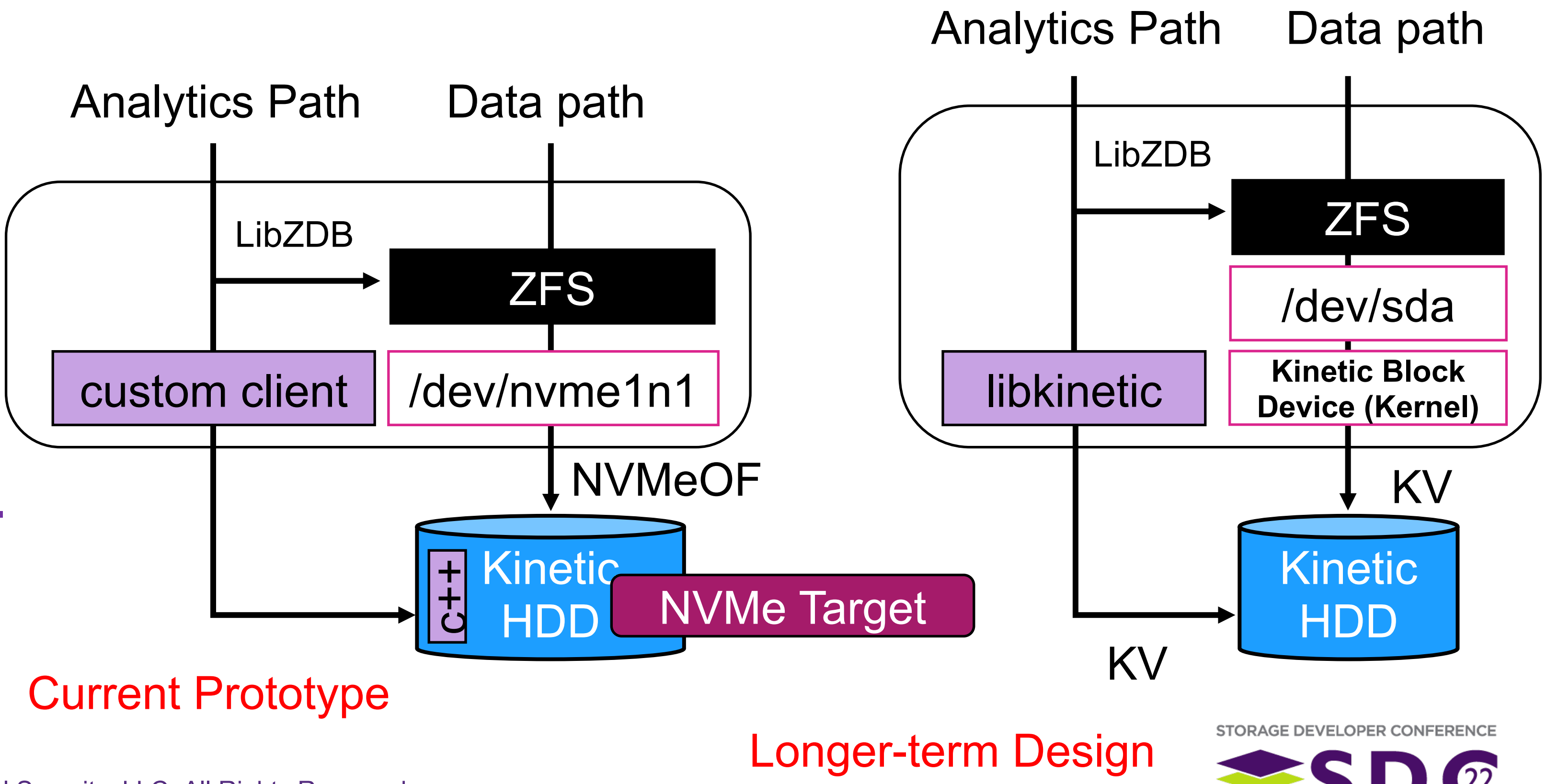
C2: LANL's Next-Gen Campaign Storage

The world's first storage system to achieve analytics on disk under erasure

Prototype Implementation

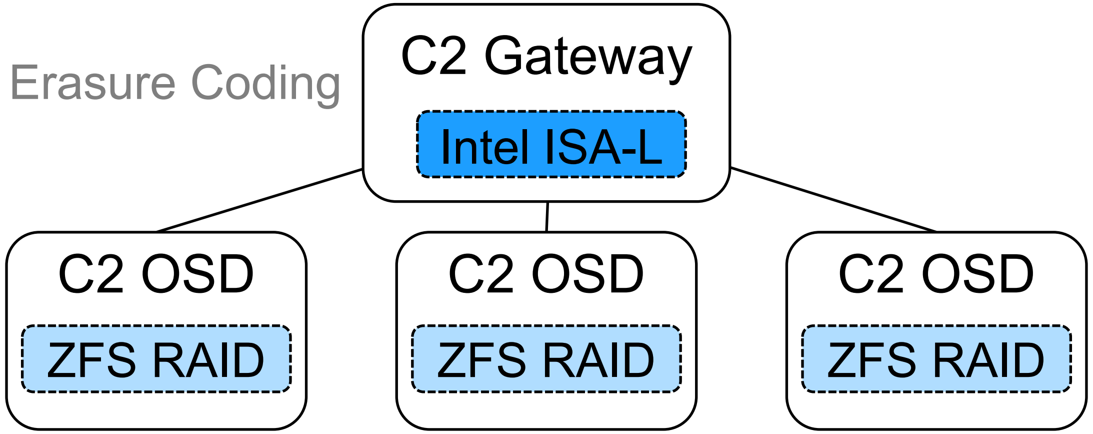


- LibZDB (LANL's stripped-down version of ZDB) for mapping ZFS filenames to disk LBAs
- Drive exposed as an NVMeOF block device to ZFS
- Custom C++ code for in-drive analytics

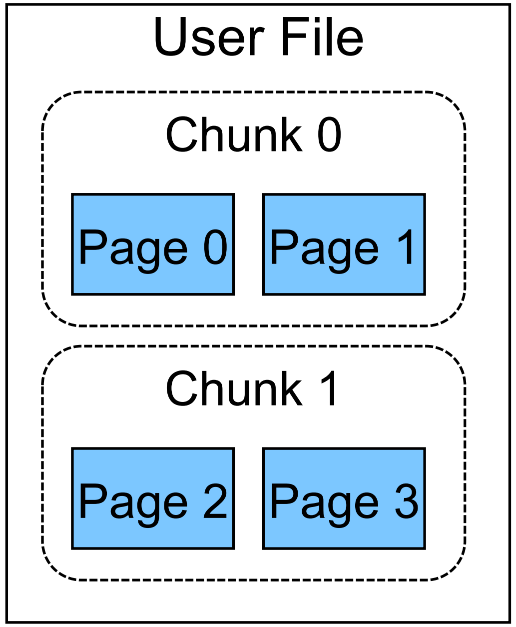


Data Format & Alignment

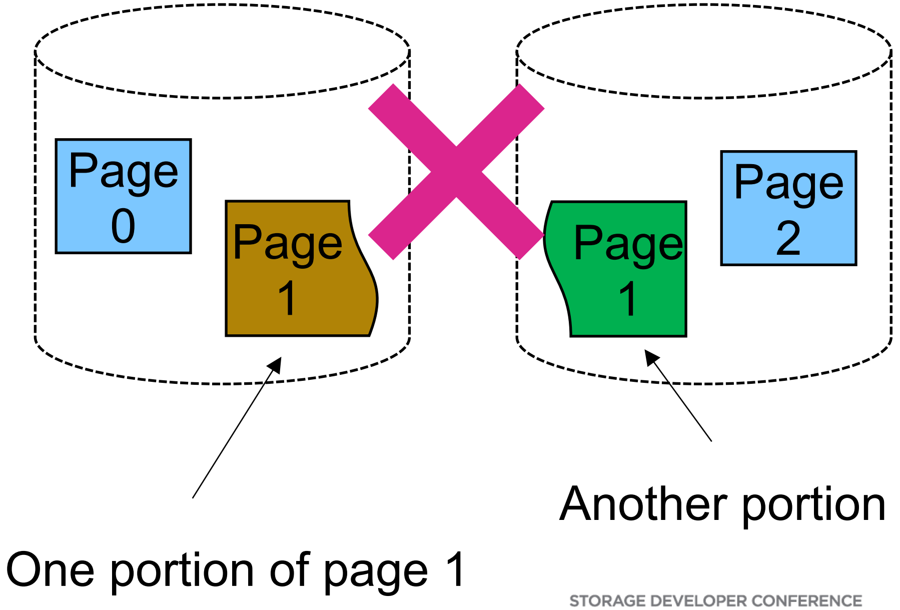
Multi-level Erasure Coding



- Many apps store data as arrays of indivisible units (that must be read in their entirety for analytics)
- Storage writes data to drives without necessarily considering unit boundaries
- A drive may not see an entire record

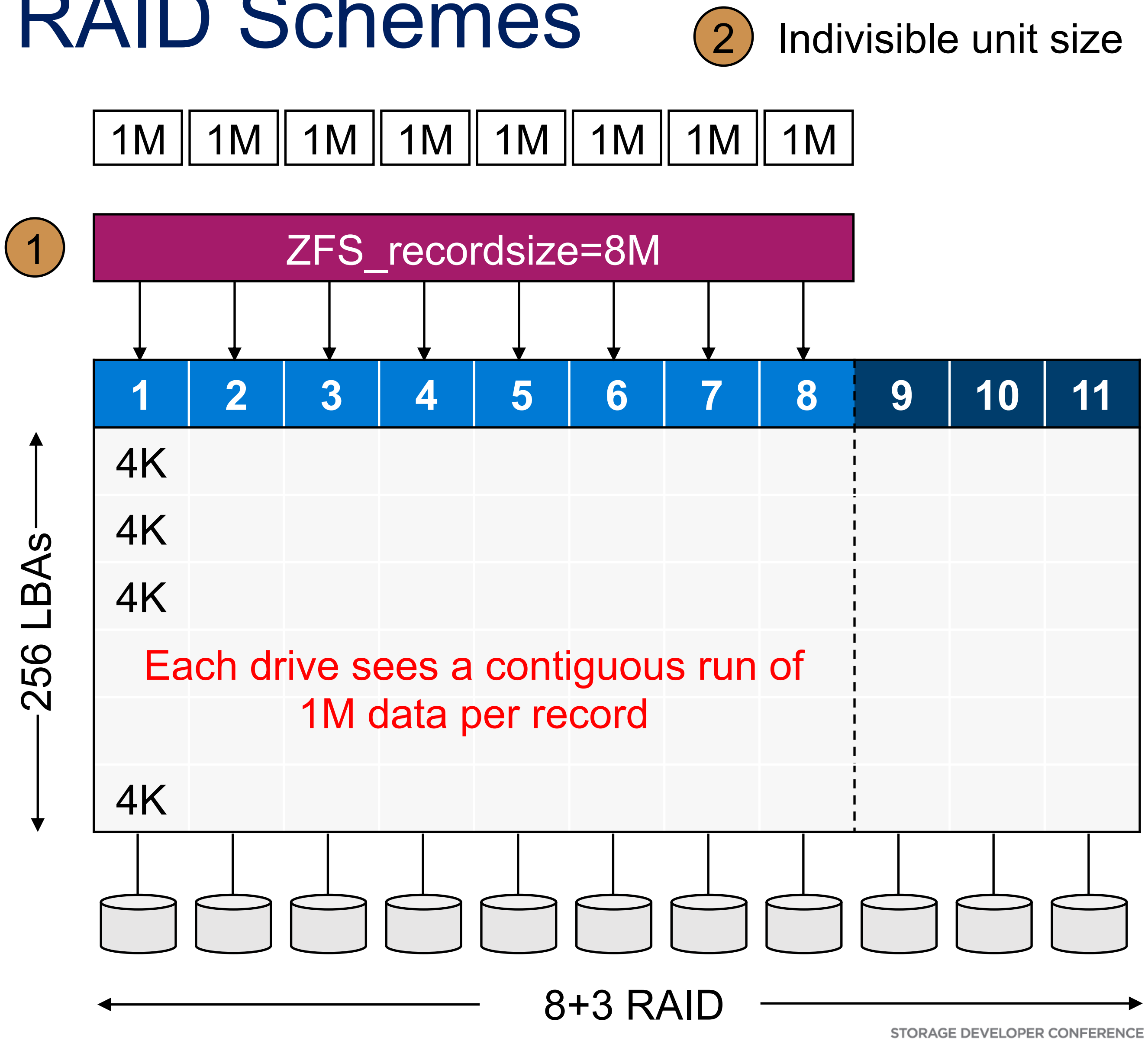


A page is split over two HDDs making in-drive computing impossible



Co-Design Data with ZFS RAID Schemes

- ZFS divides files into records (size configurable via ZFS_recordsize)
- Records are individually RAID'ed over disk drives
- Co-designing ZFS records with RAID configurations enables alignment control



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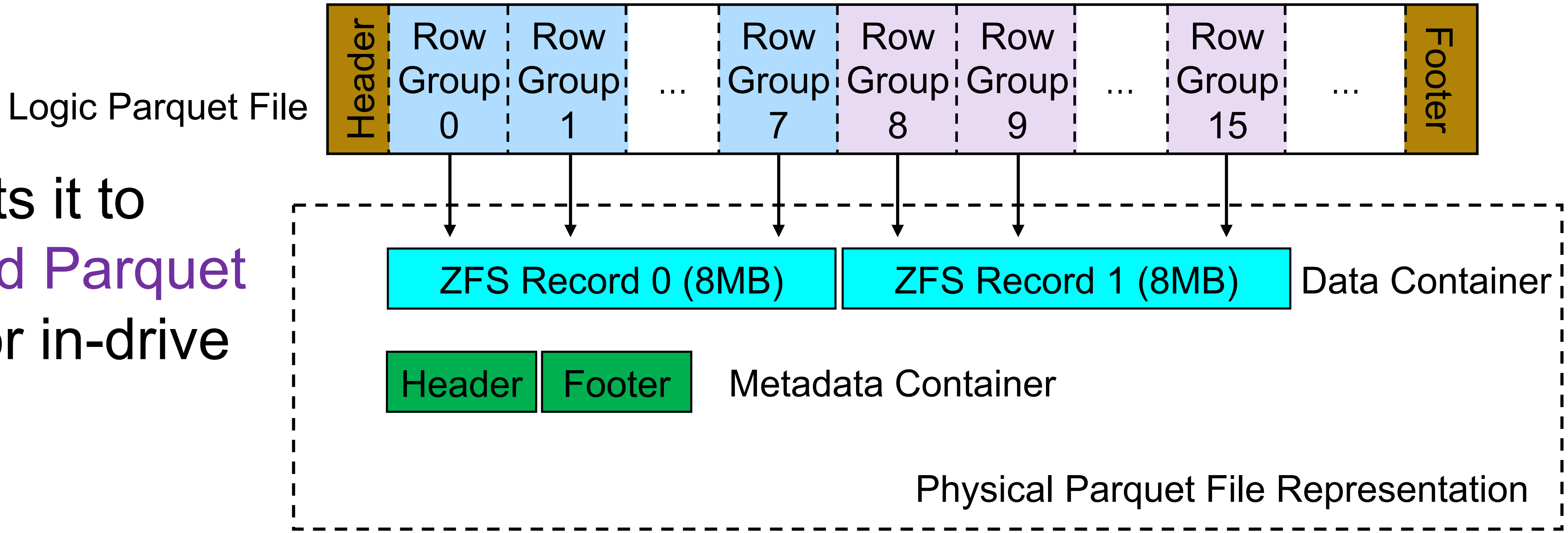
RAID-Aligned Parquet Row Groups

- App writes columnar data to C2
- C2 re-formats it to RAID-aligned Parquet row group for in-drive computation
- Each drive sees entire Parquet row groups

C2 formats each row group to be exactly 1MB and puts per row group metadata at the end of that 1MB



On ZFS, each parquet file is physically stored as a directory of 2 container files

Storage overhead due to formatting: 0.4%

Experiment: One ZFS Host, 5 Kinetic HDDs

- A particle dataset from a real-world scientific simulation: 500 million particles (24 bytes each, 12GB total)

Particle Schema

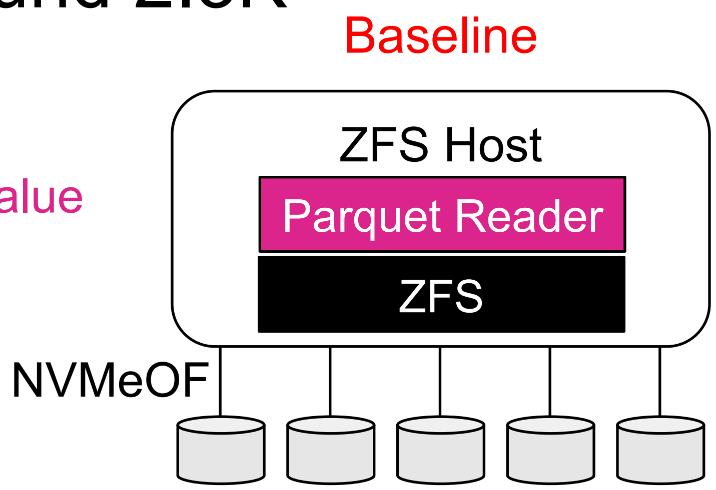
ID	X	Y	Z	Ke
uint64	float	float	float	float

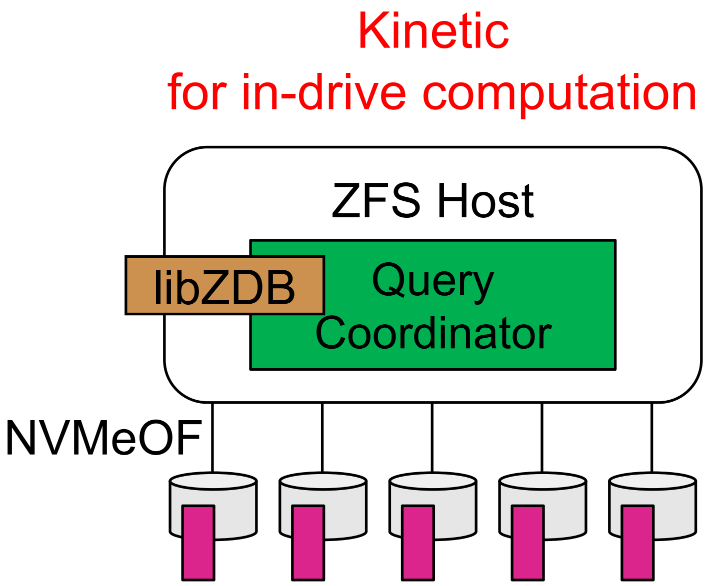
- 11K Parquet row groups (around 2.3K row groups per drive)

Query: SELECT * FROM particles WHERE Ke>Value

Ke >0.7	Ke >0.6	Ke >0.5	Ke >0.4	Ke >0.3
0	80	2.5K	63K	1104K

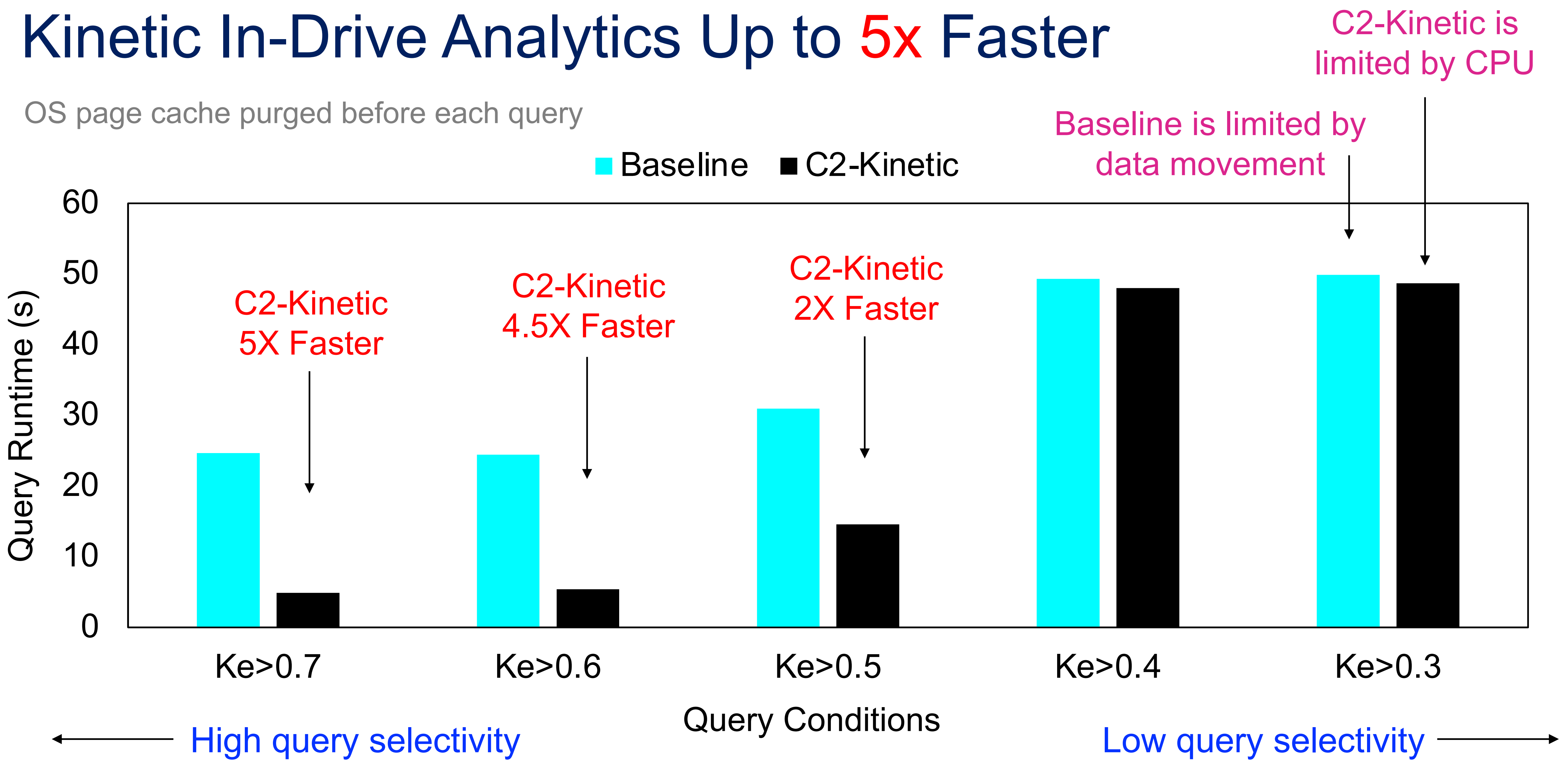
Hits per query





Kinetic In-Drive Analytics Up to 5x Faster

OS page cache purged before each query



Future Work

- Larger scale, more drives
- Asynchronous index construction in drives
- More levels of erasure coding

Conclusion

- Massive data movement has become a key bottleneck for large-scale scientific data analytics
- Near-data computation provides opportunities for rapidly searching big data with minimal data movement
- Having the flexibility to move compute to where it performs the best will become increasingly important as market evolves quickly
- C2 just demonstrated that in-drive data computation can co-exist with erasure coding while speeding up scientific discovery

LANL-Seagate Campaign Storage Design Team

- Jason Lee (jasonlee@lanl.gov)
- Brian Atkinson (batkinson@lanl.gov)
- Jarrett Crews (jarrett@lanl.gov)
- David Bonnie (dbonnie@lanl.gov)
- Dominic Manno (dmanno@lanl.gov)
- Gary Grider (ggrider@lanl.gov)
- Philip Kufeldt (philip.kufeldt@seagate.com)
- Ivan Rodriguez (ivan.rodriguez@seagate.com)
- Evan Burgess (evan.burgess@seagate.com)
- David Allen (david.j.allen@seagate.com)
- Bradley Settlemyer (bsettlemyer@nvidia.com)

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