A Survey of HPC Storage Systems

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Overview and Goals for this Lecture

1. Introduce the various types of HPC storage systems and their intended use cases
2. Survey widely-used HPC storage systems and their architectures
3. Discuss how HPC storage is evolving and potential implications for users

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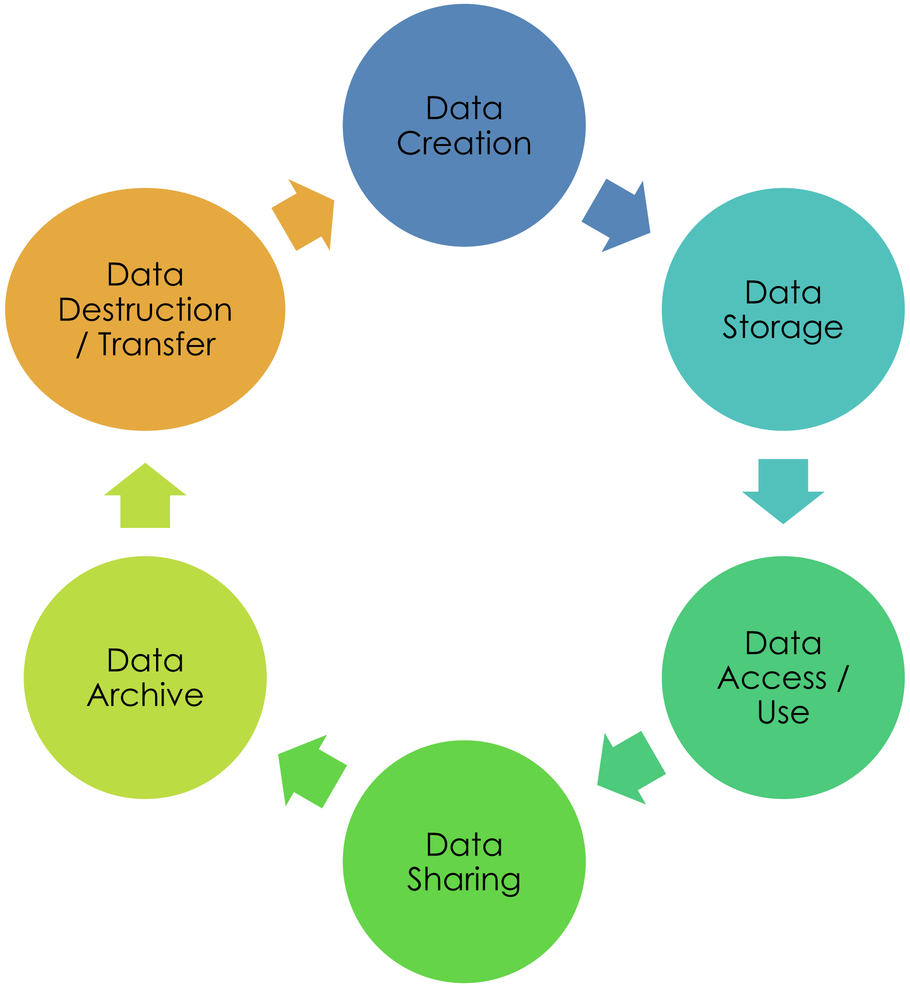
Types of HPC Storage

- Data Lifecycle
- HPC Storage Use Cases
- Storage Classification Terminology

DOE Computing Facilities Support the Full Data Lifecycle



- Creation and Access characteristics often dictate the type of Storage system on which the data is stored
- Important characteristics: (not exhaustive)
  1. Total data size
  2. Size of data in working set (% of total size)
  3. Number of processes that write/update the data
  4. Number of processes that read the data
  5. I/O access patterns, concurrency and frequency
     - *producer/consumer*: readers wait until writers are done
     - *bulk-synchronous I/O*: distinct write phases, readers see data from last completed write phase
     - *free-for-all*: no coordination between accesses from different processes (**Advice: Don't do this!**)

HPC Storage has many distinct use cases

- "Software": Facility-managed system & user software (e.g., applications, libraries, system configuration)
- "Home": Per-user or per-project storage for application code and data, job scripts, documents, etc.
- "Scratch": High-performance storage for runtime use by jobs
- "Archive": Long-term data storage for archival & sharing

- Each use case has different requirements, in terms of:
  - storage space; data security and sharing; data lifetime; I/O access pattern, concurrency and performance

HPC Storage Requirements by Use Case

Use Case	Storage Space	Storage Lifetime	Data Sharing	I/O Throughput	I/O Latency	Access Concurrency
Software	Small/Medium (10s TB)	Long-term (System Lifetime)	Yes	Low (MB/sec)	Medium	Yes (reads)
User Home	Medium (100s TB)	Medium-term (Months)	No	Medium (GB/sec)	Medium	Possibly (reads)
Project Home	Medium (100s TB)	Medium-term (Months)	Yes	Medium (GB/sec)	Medium	Likely (reads)
Scratch	Large (10s/100s PB)	Short-term (Days/Weeks)	Yes	High (TB/sec)	Low	Yes (writes and reads)
Archive	Very Large (100s PB)	Long-term (Years)	Yes	Medium (GB/sec)	High	Not Likely

Storage System Classification: Terminology

- Private vs. Shared
- Local vs. Remote
- Centralized vs. Distributed
- Serial vs. Parallel
- Single-tier vs. Multi-tier

Storage System Terminology: Private vs. Shared

- Private: storage is used by a single actor
- Shared: storage is used by many actors
- Point-of-View is important!
  - Actors may be users, compute hosts, processes, jobs, etc.
  - You can have a storage system that is private to a job, but shared amongst processes in the job

Storage System Terminology : Local vs. Remote

- Local: access to storage uses only local data paths
  - the definition of ”local data paths” can be a bit fuzzy in new HPC system architectures
  - historically, it meant “local to the host where the process performing the access is located”

- Remote: access to storage is via the network

Storage System Terminology : Centralized vs. Distributed

- Centralized: a client interacts with a single storage server
- Distributed: a client may interact with many storage servers

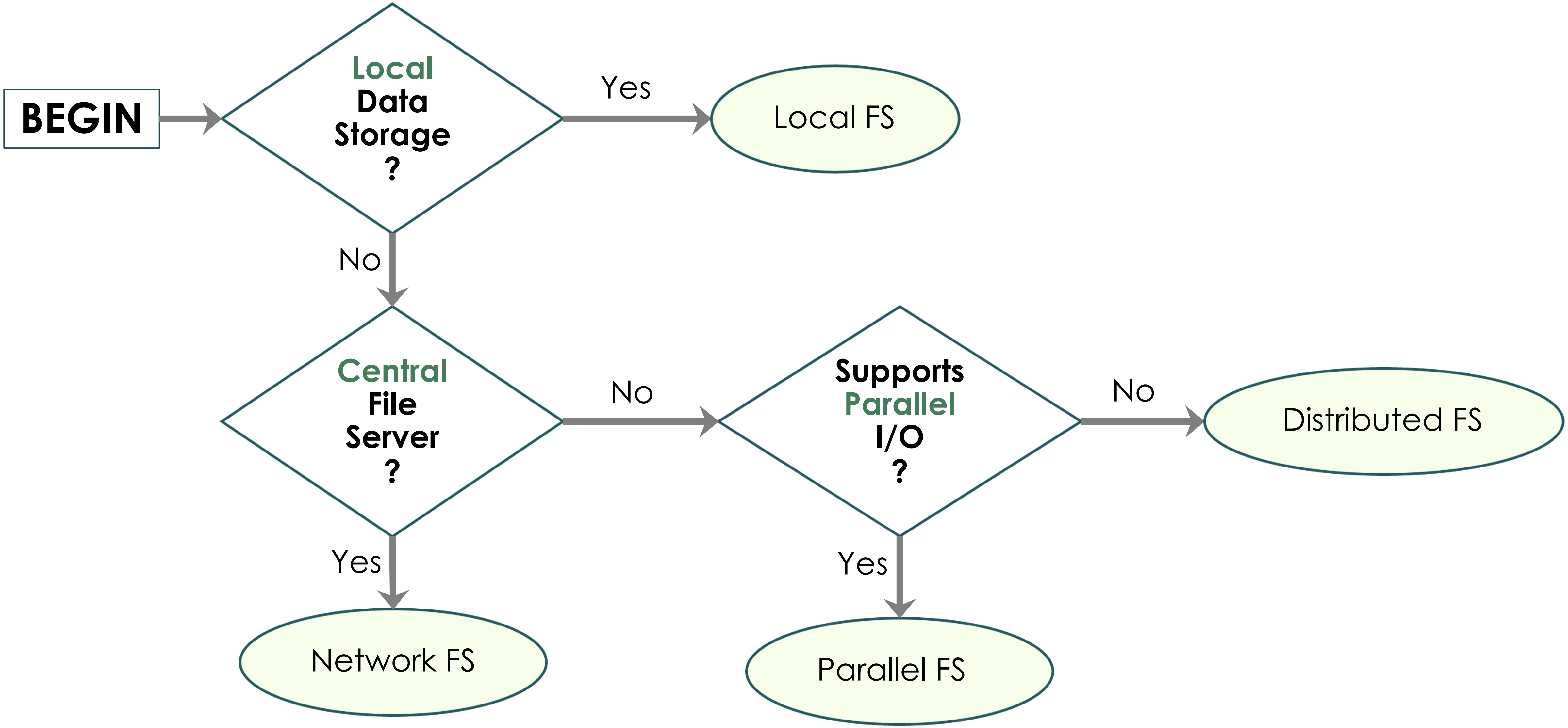
Storage System Terminology : Serial vs. Parallel

- Serial: a single client accesses a particular data item (e.g., a file) on the storage at any given time
  - serial accesses can be made by separate clients, they just don't overlap in time
- Parallel: many clients access a particular data item at the same time

Storage System Terminology : Single-Tier vs. Multi-Tier

- Single-Tier:
  - Physical: a storage system includes one layer of storage devices
  - Logical: clients interact with a single storage system
- Multi-Tier:
  - Physical: a storage system includes multiple layers of storage devices
  - Logical: clients have access to two or more storage systems

Storage Terminology Example: Shared File Systems



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Survey of HPC Storage Systems by Use Case

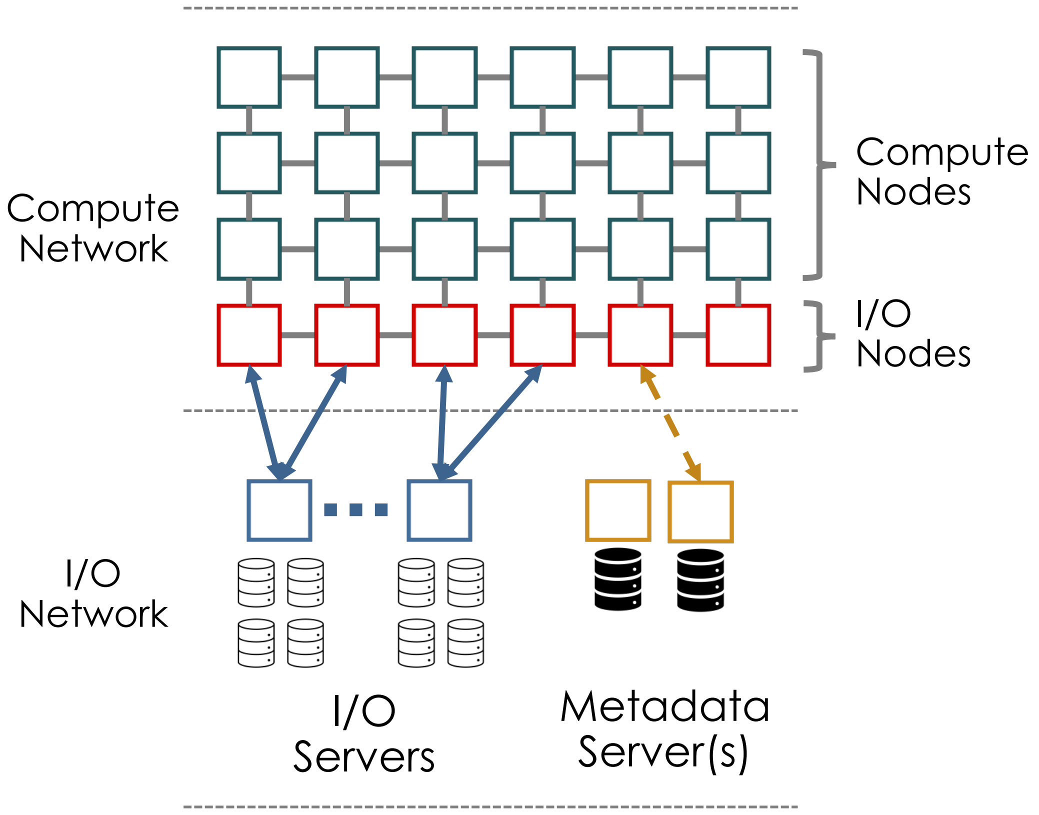
- Scratch Storage
- Home Storage
- Software Storage
- Archive Storage

Scratch Storage Systems

- Purpose: High-performance, short-term storage for runtime use by HPC jobs
- Common Solutions
  – Parallel File Systems (PFS)
  – Burst Buffers (BB)
  – Node-local Storage (NLS)

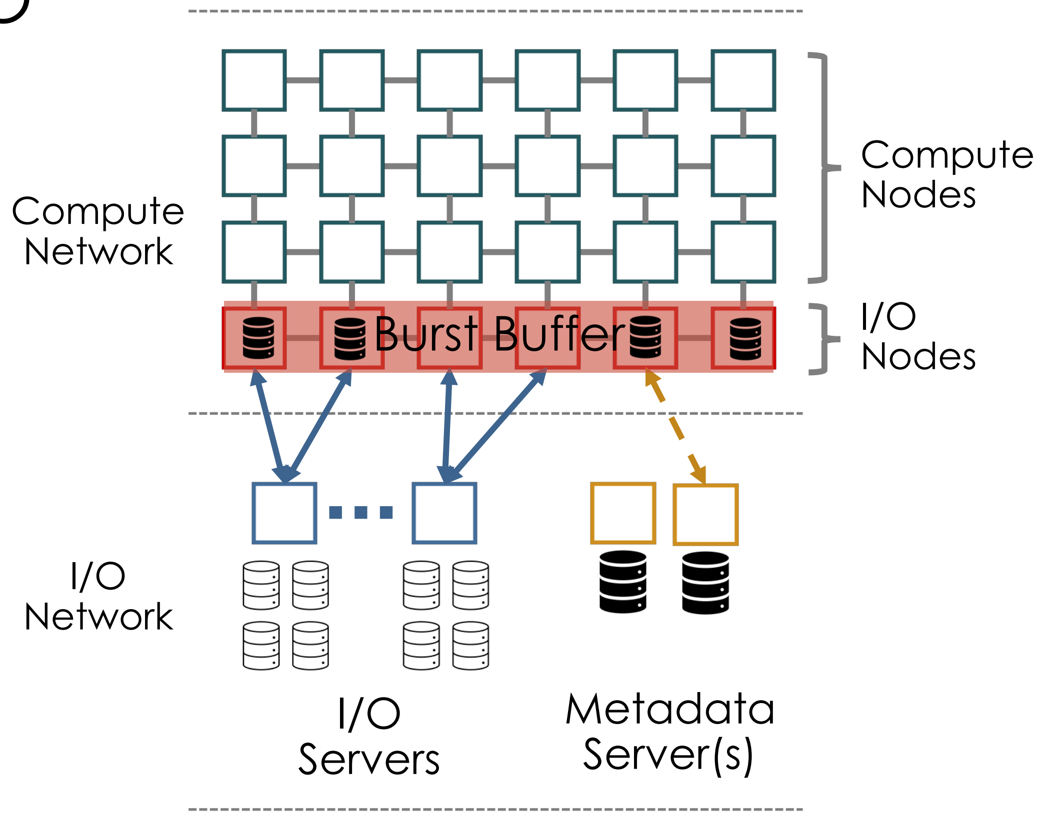
Scratch Storage - Parallel File Systems

- Goal: Enable high-performance I/O for a large number of concurrent clients
- Production Examples: Lustre, IBM Spectrum Scale (GPFS), Panasas PanFS
- Key Architectural Features
  - separate FS metadata and I/O servers
    - "do one thing well"
  - spread file data across I/O servers
    - helps to load balance I/O traffic
  - clients directly access I/O servers in parallel
    - helps to maximize I/O bandwidth



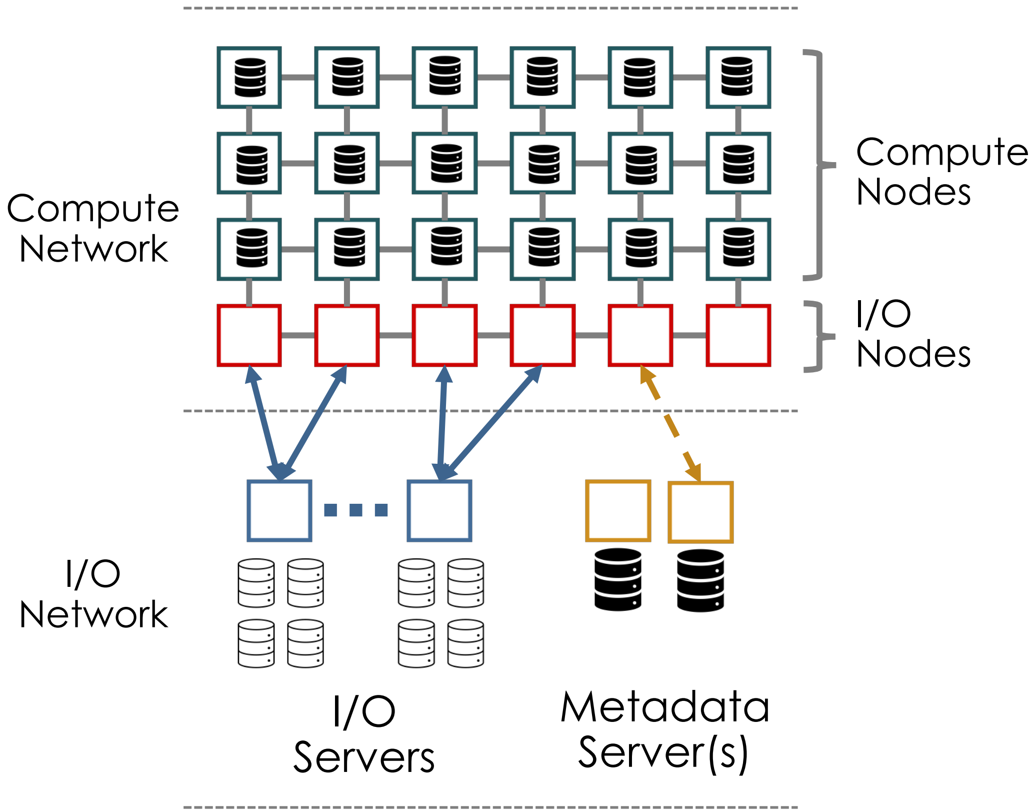
Scratch Storage - Burst Buffers

- Goal: Reduce load on a parallel file system to enable faster application I/O
  - by buffering bursty writes (e.g., simulation outputs or checkpoints)
  - by caching data from "hot" reads
- Production Examples: Cray DataWarp
- Key Architectural Features
  - "Faster" storage (e.g., Flash SSD) closer to Compute
  - Automatic data staging to/from PFS
  - Reservation-oriented (e.g., resources dedicated to specific jobs)



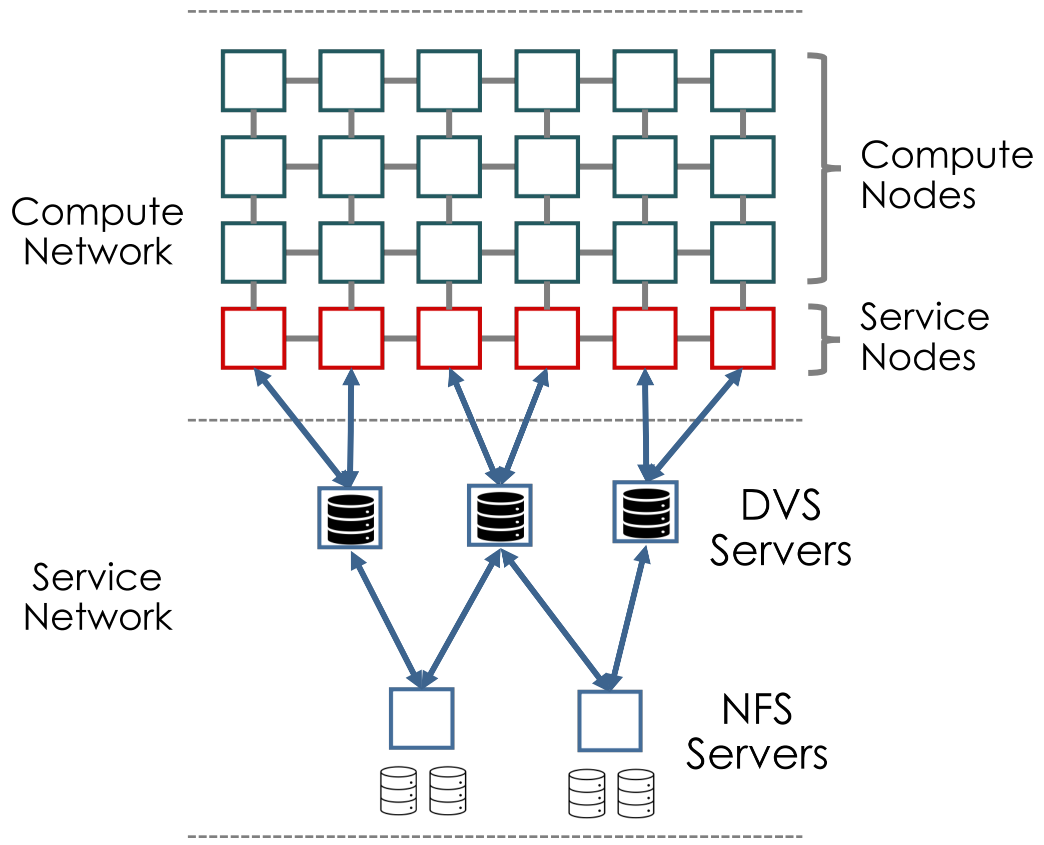
Scratch Storage - Node-local Storage

- Goal: Reduce load on a parallel file system to enable faster application I/O
  - by buffering bursty writes (e.g., simulation outputs or checkpoints)
  - by pre-staging data for "hot" reads
- Production Examples: NVMe SSDs in compute nodes
- Key Architectural Features
  - "Fastest" storage co-located with Compute
  - Storage capability scales linearly with allocated job nodes
  - However, software solutions required for:
    - runtime sharing of data in NLS across nodes (e.g., UnifyFS)
    - moving data to/from PFS



Home Storage Systems

- Purpose: User or Project storage
- Common Solutions
  - Network File Systems
    - Production Examples: NFSv4
  - Distributed File Systems
    - Production Examples: HPE/Cray Data Virtualization Service (DVS)
  - Parallel File Systems
    - Production Examples: Lustre, GPFS



Software Storage Systems

- Purpose: Facility-managed system & user software
- Common Solutions
  - Local File System
    - Production Examples: sys/app software cache on NLS
  - Network File Systems
    - Production Examples: NFSv4
  - Distributed File Systems
    - Production Examples: HPE/Cray DVS
  - Parallel File Systems
    - Production Examples: Lustre, GPFS

Archive Storage Systems

- Purpose: Long-term data storage for archival & sharing
- Common Solutions
  - Tape Libraries
  - High Performance Storage System (HPSS)
    - software optimized for efficient and performant use of tape libraries
    - also supports classes of different storage media and hierarchical tiering

Survey Summary: Storage @ DOE Computing Facilities

Center	Home	Software	Scratch	Archive
ALCF	Lustre	Lustre	Lustre, NLS	HPSS
NERSC	GPFS[1]	GPFS[1]	Lustre	HPSS
OLCF	NFS	NFS, DVS[2], NLS	GPFS[1], Lustre, NLS	HPSS

[1]NOTE: IBM Spectrum Scale is the product name for GPFS.

[2]NOTE: DVS is the Cray Data Virtualization Service.

HPC Storage is Evolving

- HPC Storage Challenges
- Requirements Driving Evolution
- HPC Storage Architecture Trends

Challenge: Exascale Systems have Arrived

- For 30+ years, DOE HPC meant scalable modeling and simulation
  - bulk-synchronous checkpoint/restart (C/R) was the primary I/O requirement (write-dominated, mostly sequential accesses)
    - PFS are designed to do C/R well, while still providing POSIX I/O semantics
- C/R for full-scale applications on exascale systems is problematic
  - expected system component failure rates require more frequent checkpoints for application progress
  - number of potential I/O clients exceeds the capabilities of most PFS

Challenge: Data-intensive Science is Widespread

- Data-intensive Science is pushing the current limits of HPC Storage
- Large-scale data analysis (e.g., ML model training) is read-dominated, and often uses repeated random accesses from varying processes
- Experimental data from instruments with very large data generation rates (e.g., LHC, SKA) is currently difficult/impossible to store in lossless form

HPC Storage Evolution - New Requirements

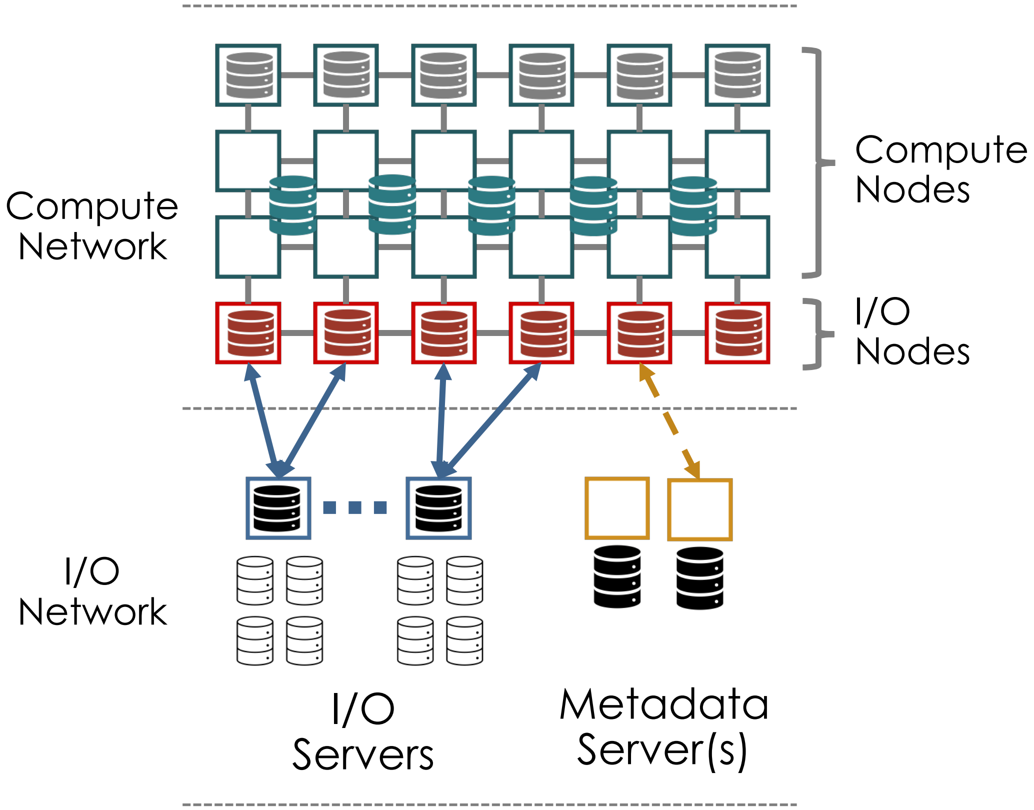
- Interfaces and Access Patterns
  - Reads are as important as writes (maybe more important)
  - POSIX file read/write is rarely the right I/O semantic for scalable HPC workloads
    - many workloads may benefit from alternatives such as:
      - simple put/get of data objects, possibly with object versioning
      - publish/subscribe
      - streaming data

HPC Storage Evolution - New Requirements

- Storage advances from the cloud may be beneficial to HPC
  - and are frequently integral to deployment of popular data analysis frameworks on HPC systems
- Cloud Data Abstractions and Interfaces
  - Key-value and columnar data stores are better suited for many data analysis workloads involving queries
  - Graph analysis benefits from custom storage
  - Analysis of real-time streaming data from many sources
- Cloud Storage Technologies
  - Elastic provisioning of storage resources
  - Quality-of-service (QoS) or service-level agreements (SLA)

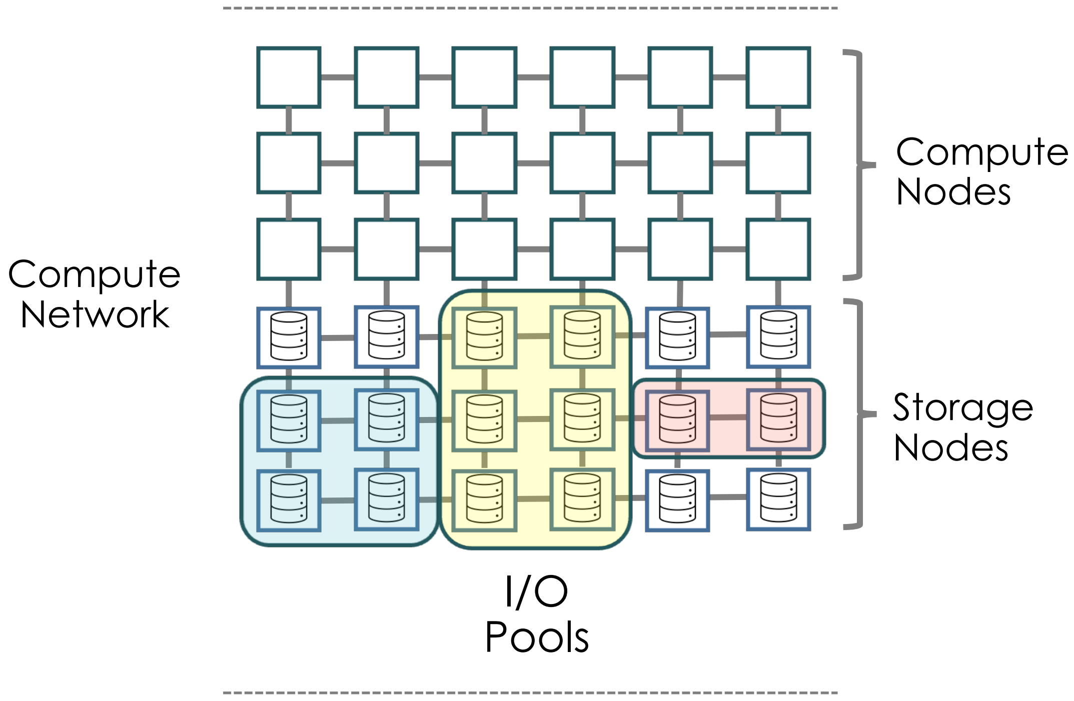
Storage Architecture Trends - Tiering for Performance

- More use of "fast" non-volatile memory-based storage devices
  - including hardware optimized for key-value or put/get semantics
- More storage tiers
  - within HPC PFS and Archive (mostly transparent to users)
  - between HPC Compute and PFS (multi-tier burst buffers)
  - within HPC Compute (node-local storage, near-node-local storage)



Storage Architecture Trends - Storage Disaggregation

- Storage disaggregation
- Allocate network-attached storage resources dynamically to pools
  - pools provide raw I/O on blocks or objects, not POSIX
- Assign pools to jobs
- Pools may also provide storage QoS guarantees



HPC Storage User Advice

"This all sounds very confusing. How do you expect users to deal with such complexity?"

- HPC I/O libraries provide higher-level abstractions for managing and accessing scientific data (e.g., hierarchical groups of datasets)
  - HPC storage experts are busily trying to hide all this complexity under the covers of the existing I/O libraries
- Vendors are also developing new storage abstractions and interfaces that help manage the complexity (e.g., DAOS)

Discussion/Questions

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