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
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

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

BEGIN

Local Data Storage?

Yes: Local FS

No: Central File Server?

Yes: Network FS

No: Supports Parallel I/O?

Yes: Parallel FS

No: Distributed FS
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

<table>
<thead>
<tr>
<th>Center</th>
<th>Home</th>
<th>Software</th>
<th>Scratch</th>
<th>Archive</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALCF</td>
<td>Lustre</td>
<td>Lustre</td>
<td>Lustre, NLS</td>
<td>HPSS</td>
</tr>
<tr>
<td>NERSC</td>
<td>GPFS(^1)</td>
<td>GPFS(^1)</td>
<td>Lustre</td>
<td>HPSS</td>
</tr>
<tr>
<td>OLCF</td>
<td>NFS</td>
<td>NFS, DVS(^2), NLS</td>
<td>GPFS(^1), Lustre, NLS</td>
<td>HPSS</td>
</tr>
</tbody>
</table>

\(^1\)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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