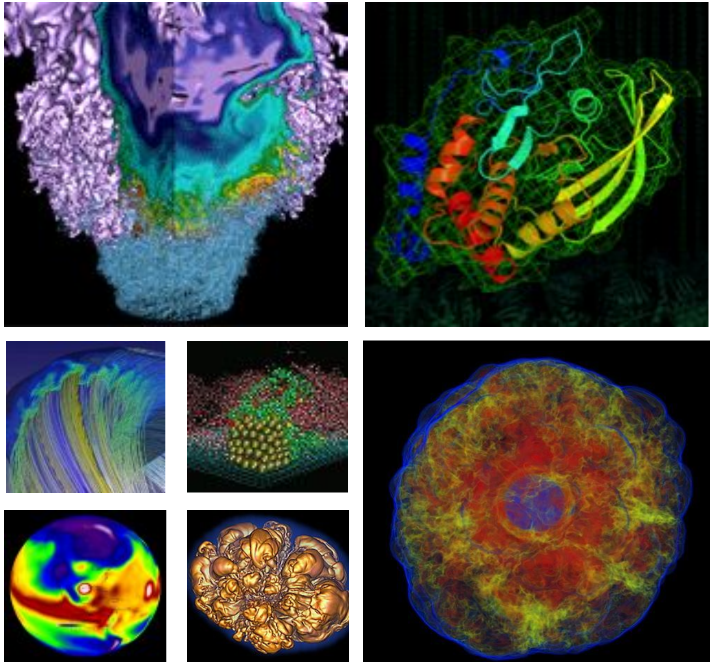
Designing an All-Flash Lustre File System for the 2020 NERSC Perlmutter System



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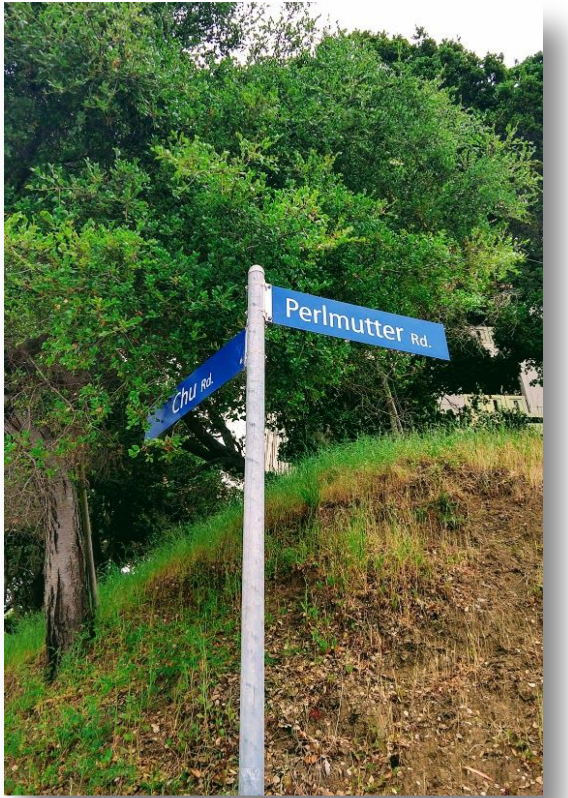
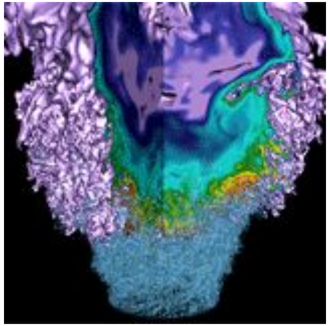
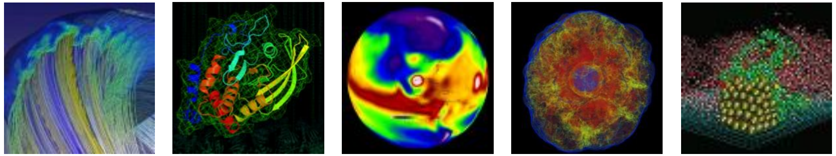
Agenda

- Introduction and Methods
    - NERSC / N-8 / N-9 / Motivation
    - Reference System (Cori)
    - New System (Perlmutter)
- File System Capacity
- Drive Endurance
    - Parity and Write Amplification
    - Anticipated Write Load
    - Endurance Requirements
- Metadata Configuration
    - MDT Capacity Required by DOM
    - MDT Capacity Required for Inodes
    - Overall MDT Capacity
- Conclusion



NERSC + Systems Overview

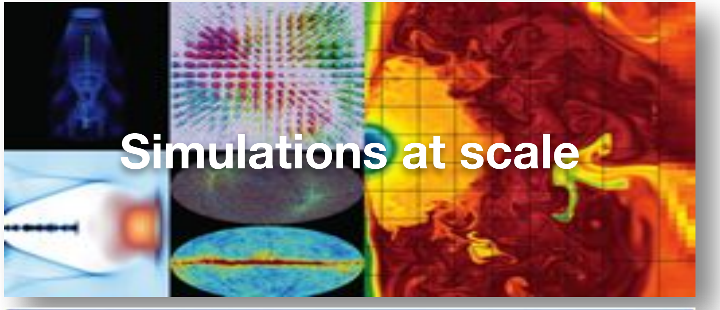




NERSC

NERSC @ Berkeley Lab (LBNL)

- **NERSC is the mission HPC computing center for the DOE Office of Science**
- **HPC and data systems for the broad Office of Science community**
- **7,000 Users, 870 Projects, 700 Codes**
- **>2,000 publications per year**
- **2015 Nobel prize in physics supported by NERSC systems and data archive**
- **Diverse workload type and size**
    - Biology, Environment, Materials, Chemistry, Geophysics, Nuclear Physics, Fusion Energy, Plasma Physics, Computing Research
- **New experimental and AI-driven workloads**



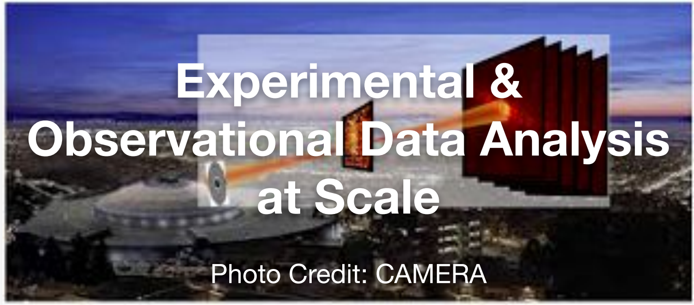


Photo Credit: CAMERA

NERSC-8 aka Cori (Cray XC-40)

Compute

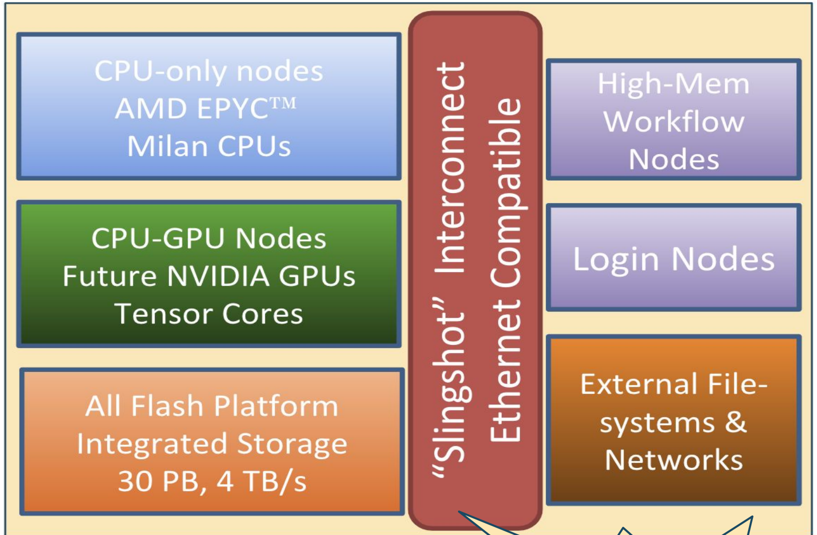
- 9,688 Intel KNL nodes
- 2,388 Intel Haswell nodes

Storage

- 30 PB, 700 GB/s scratch
  - Lustre (Cray ClusterStor)
  - 248 OSSes x 41 HDDs x 4 TB
  - 8+2 RAID6 declustered parity
- 1.8 PB, 1.5 TB/s burst buffer
  - Cray DataWarp
  - 288 BBNs x4 SSDs x 1.6 TB
  - RAID0

NERSC-9 aka Perlmutter

- Designed for both large scale simulation and data analysis from experimental facilities
- Overall 3x to 4x capability of Cori
- Includes both NVIDIA GPU-accelerated and AMD CPU-only nodes
- Slingshot Interconnect
- Single Tier, All-Flash Lustre scratch filesystem



CPU-only nodes
AMD EPYC™
Milan CPUs

CPU-GPU Nodes
Future NVIDIA GPUs
Tensor Cores

All Flash Platform
Integrated Storage
30 PB, 4 TB/s

"Slingshot" Interconnect
Ethernet Compatible

High-Mem
Workflow
Nodes

Login Nodes

External File-systems &
Networks

Delivery in late-2020

Multiple Storage Tiers

Lustre “scratch” and Burst Buffer

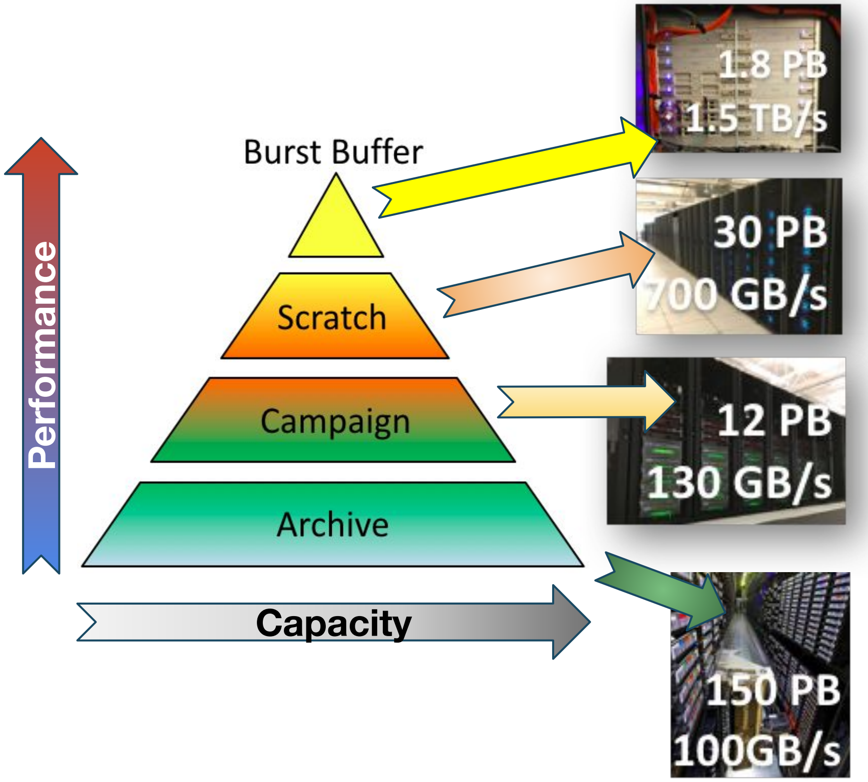
- Ephemeral storage, data purged if not accessed, user-based quotas and permissions
- Intended for high speed access to active data used for running computations

Spectrum Scale “project” file system

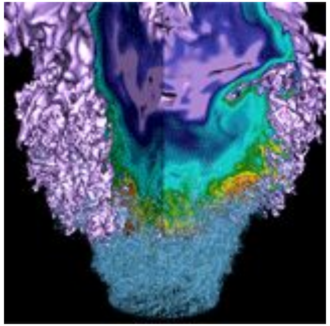
- Medium term storage, data never purged, group quota and permissions
- Intended for shared data needed by entire science group, will be used for computing in the near future

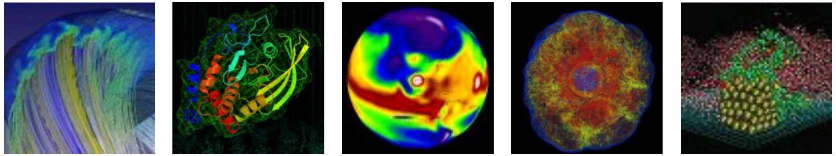
HPSS Tape Archive

- Long term storage, data never purged, user-based and group quotas and permissions
- Permanent archival of scientific data



Introduction + Methods





Introduction + Methods

Today, it is economically possible to deploy enough flash capacity to replace the scratch tier and burst buffer tier

- How much capacity is enough capacity for a scratch file system?
- What should the purge policy be to manage this capacity?
- Will the SSDs wear out too quickly?
- What drive endurance rating is required?

Introduction + Methods

- Quantitative approach to design the 30 PB all-flash Lustre file system
- Integrated analysis of *current* workloads and *projections* of future performance and throughput
- We were able to constrain many critical design space parameters and quantitatively demonstrate that Perlmutter will deliver
  - Optimal performance
  - Effectively balance cost
  - Effectively balance capacity
  - Endurance
  - Modern features of Lustre

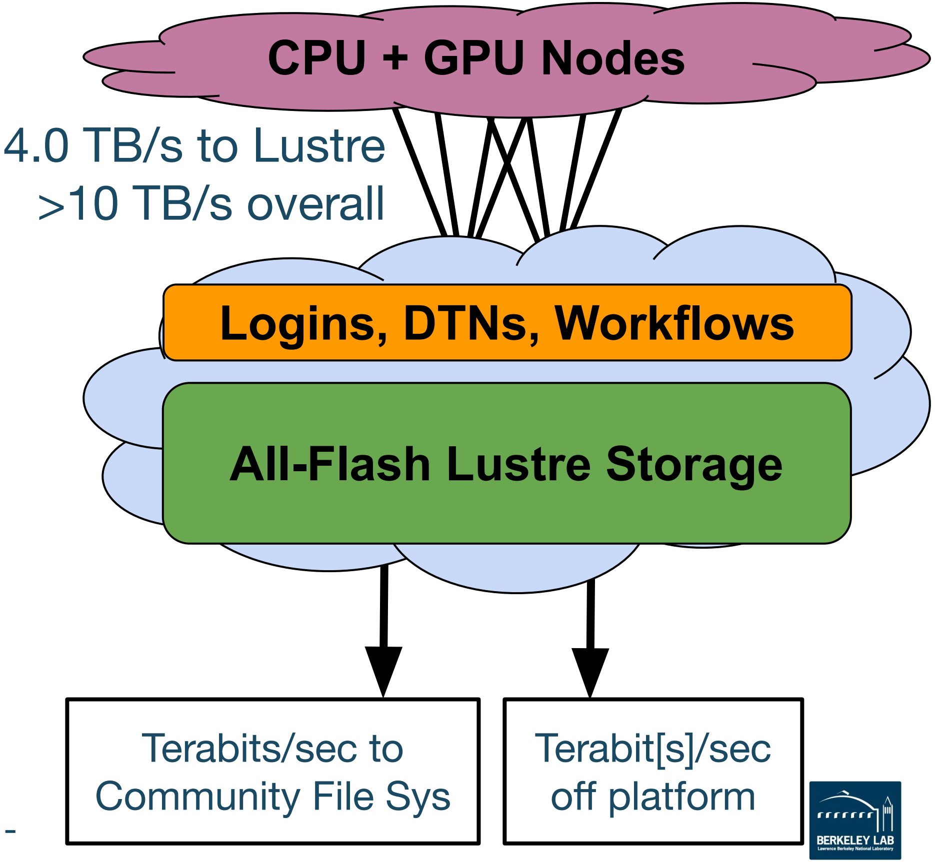
NERSC-9's All-Flash Architecture

Fast across many dimensions

- 30 PB usable capacity
- ≥ 4 TB/s sustained bandwidth
- ≥ 7,000,000 IOPS
- ≥ 3,200,000 file creates/sec

Integrated network, separate groups

- Storage/logins remain up when compute is down
- No LNET routers between compute and storage



CPU + GPU Nodes

4.0 TB/s to Lustre
>10 TB/s overall

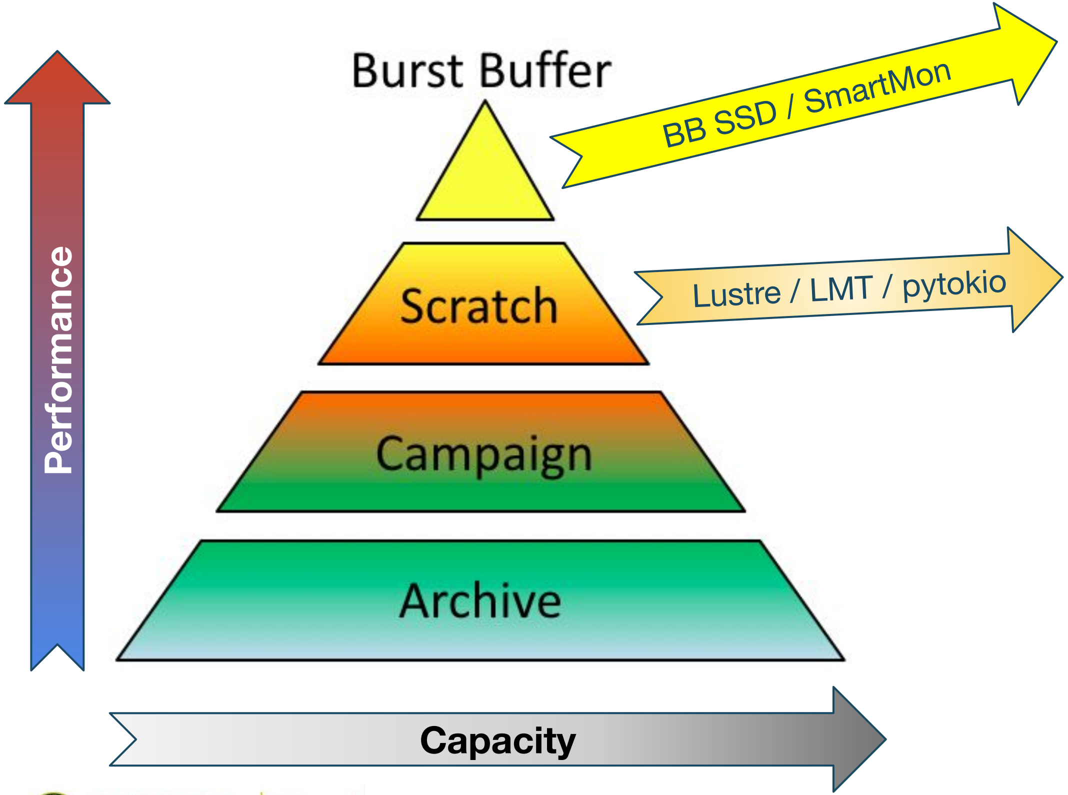
Logins, DTNs, Workflows

All-Flash Lustre Storage

Terabits/sec to Community File Sys

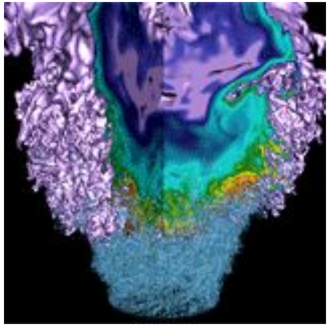
Terabit[s]/sec off platform

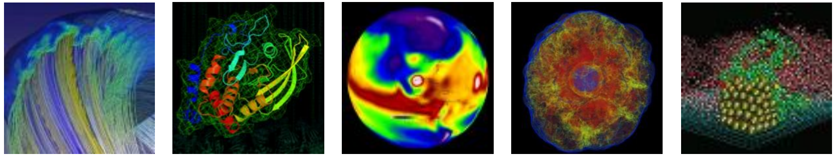
Analysis Tools Used



- **SmartMon tools (Intel Data Center SSD Tool)**
  - Device-level data including the total bytes read and written, and the total bytes read and written to NAND
- **Lustre Monitoring Tool (LMT)**
  - Total number of bytes read and written to each Lustre object storage target (OST)
  - pytokio preserves all LMT data
- **Capacity growth**
  - Lustre "lfs df"
- **Robinhood**
  - The distribution database of file and inode sizes

File System Capacity





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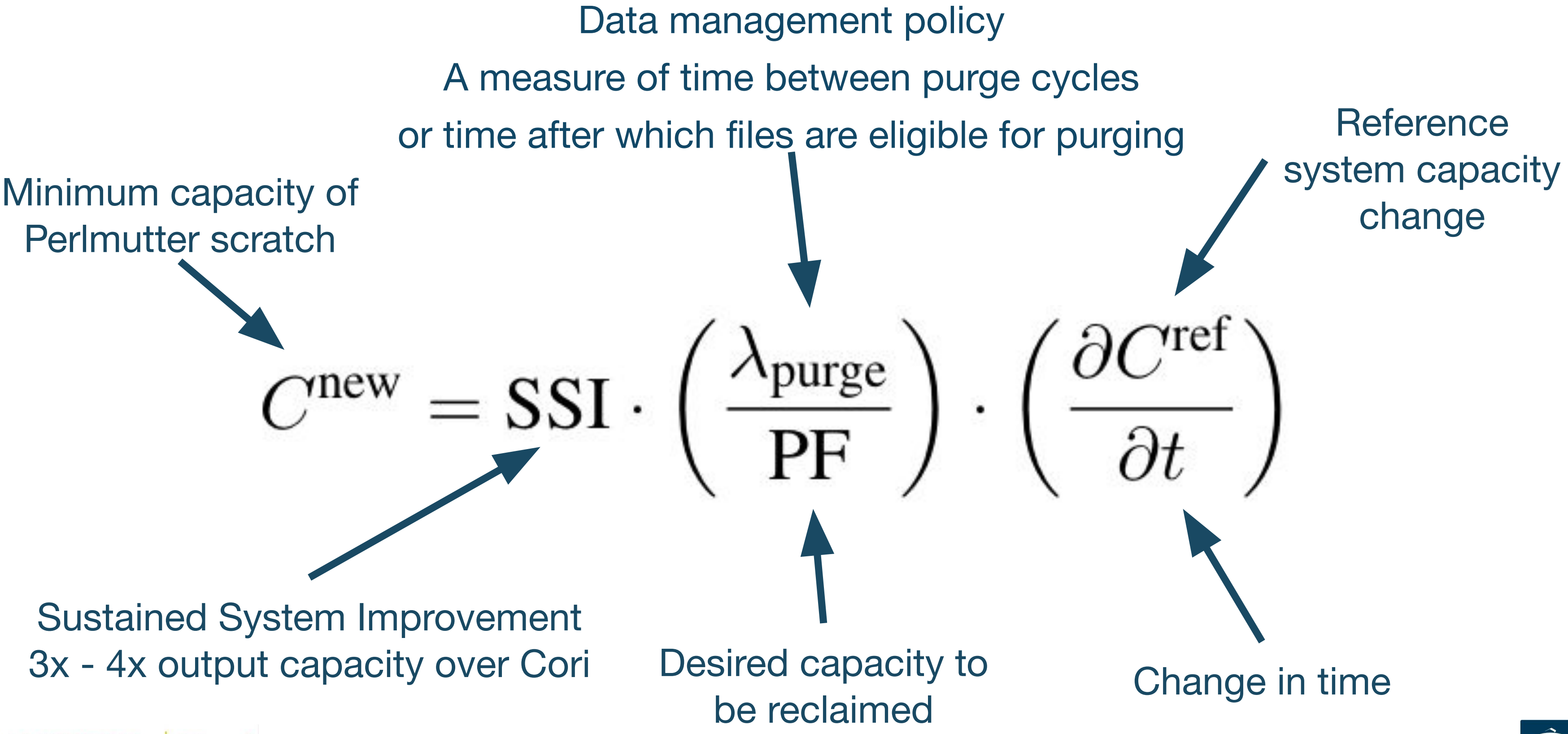

Data management policy

A measure of time between purge cycles or time after which files are eligible for purging

Reference system capacity change

Minimum capacity of Perlmutter scratch

$$C^{\text{new}} = \text{SSI} \cdot \left(\frac{\lambda_{\text{purge}}}{\text{PF}} \right) \cdot \left(\frac{\partial C^{\text{ref}}}{\partial t} \right)$$

Sustained System Improvement
3x - 4x output capacity over Cori

Desired capacity to be reclaimed

Change in time

File System Capacity

$\left(\frac{\partial C^{\mathrm{ref}}}{\partial t}\right)$ Mean daily growth projected for Perlmutter at 133 TB/day

$\left(\frac{\lambda_{\mathrm{purge}}}{\mathrm{PF}}\right)$ Data retention policy for Perlmutter is `atime` > 28 days

- OK to purge after that time
- Each purge aims to remove or migrate 50% of the total capacity

SSI Anticipated 3x to 4x sustained system improvement

C^{new} **Minimum Perlmutter capacity is between 22 PB and 30 PB**

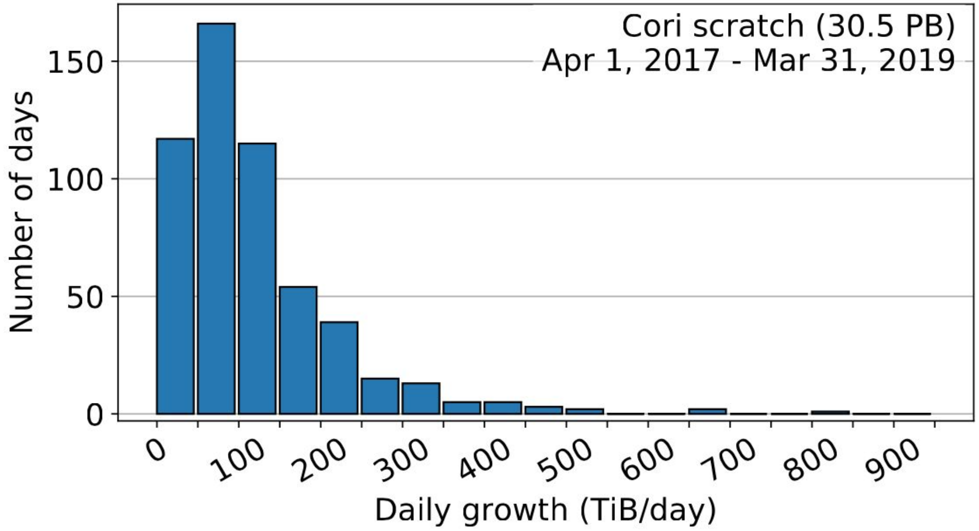

Figure 1 - Distribution of daily growth of Cori's scratch

File System Capacity

$\left(\frac{\partial C^{\text{ref}}}{\partial t}\right)$ Me ojected for Pe day

We set

$\left(\frac{\lambda_{\text{purge}}}{\text{PF}}\right)$ Data retention policy for Perlmutter is `atime` > 28 days

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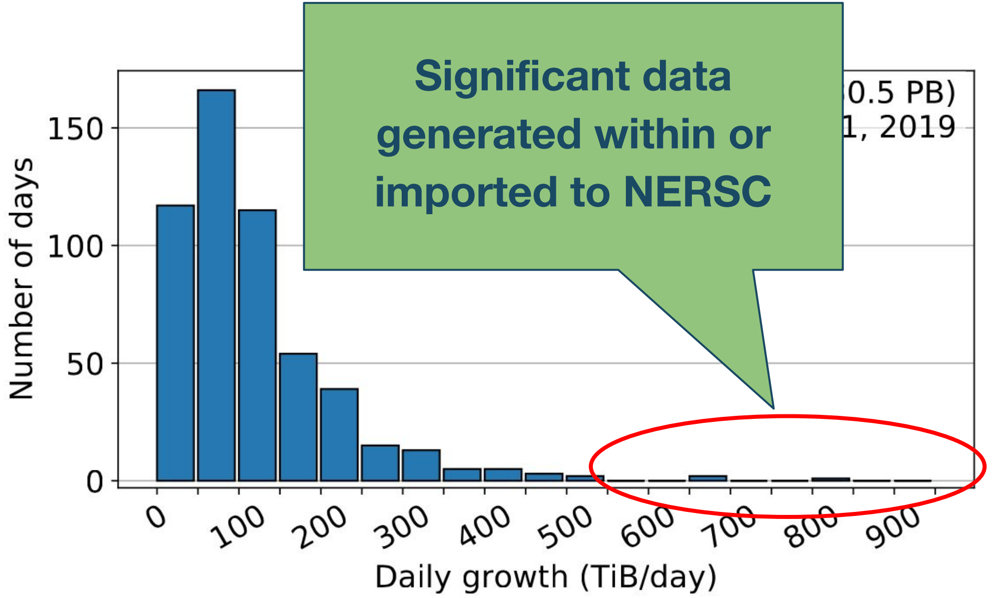
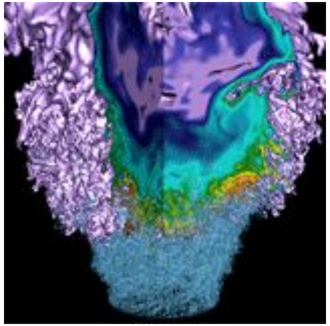
Set

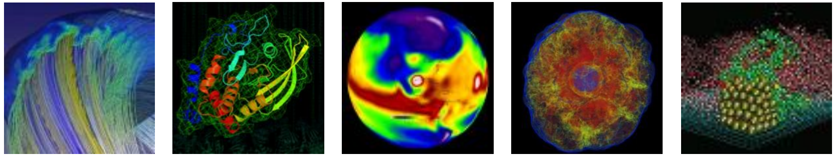


Significant data generated within or imported to NERSC

Figure 1 - Distribution of daily growth of Cori's scratch

Drive Endurance





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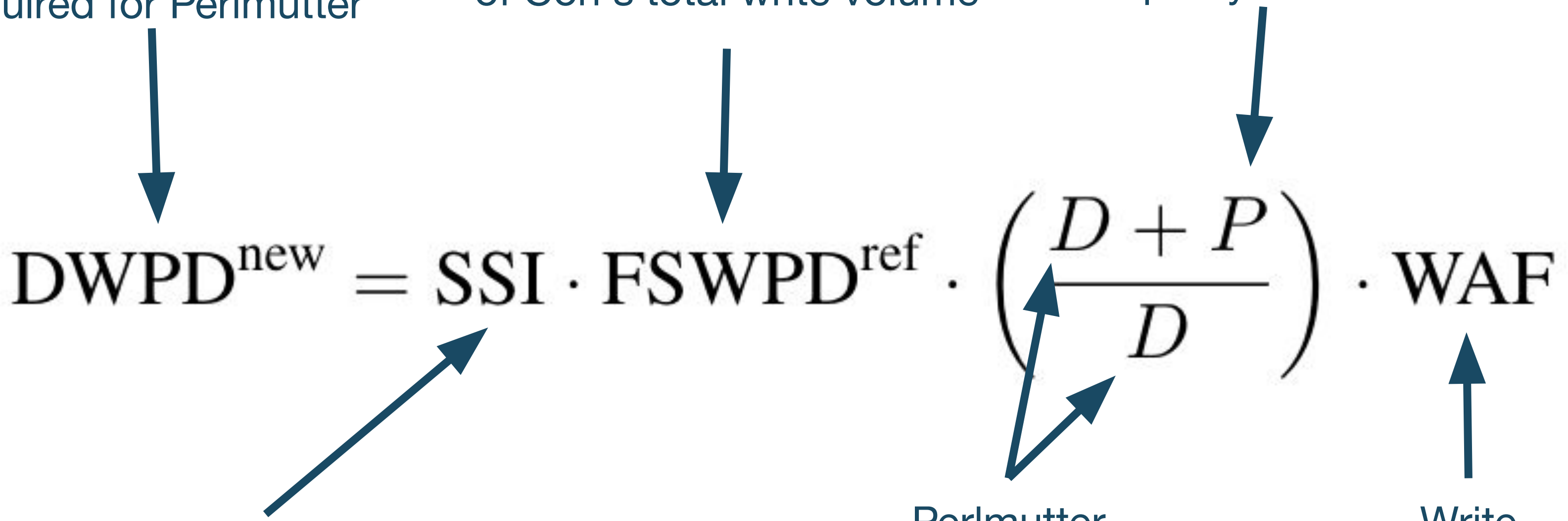


Drive Writes Per Day required for Perlmutter

File System Writes Per Day of Cori's total write volume

Perlmutter parity blocks

$$\mathrm{DWPD}^{\mathrm{new}} = \mathrm{SSI} \cdot \mathrm{FSWPD}^{\mathrm{ref}} \cdot \left(\frac{D+P}{D}\right) \cdot \mathrm{WAF}$$

Sustained System Improvement 3x - 4x output capacity over Cori

Perlmutter data blocks

Write Amplification Factor

Drive Endurance

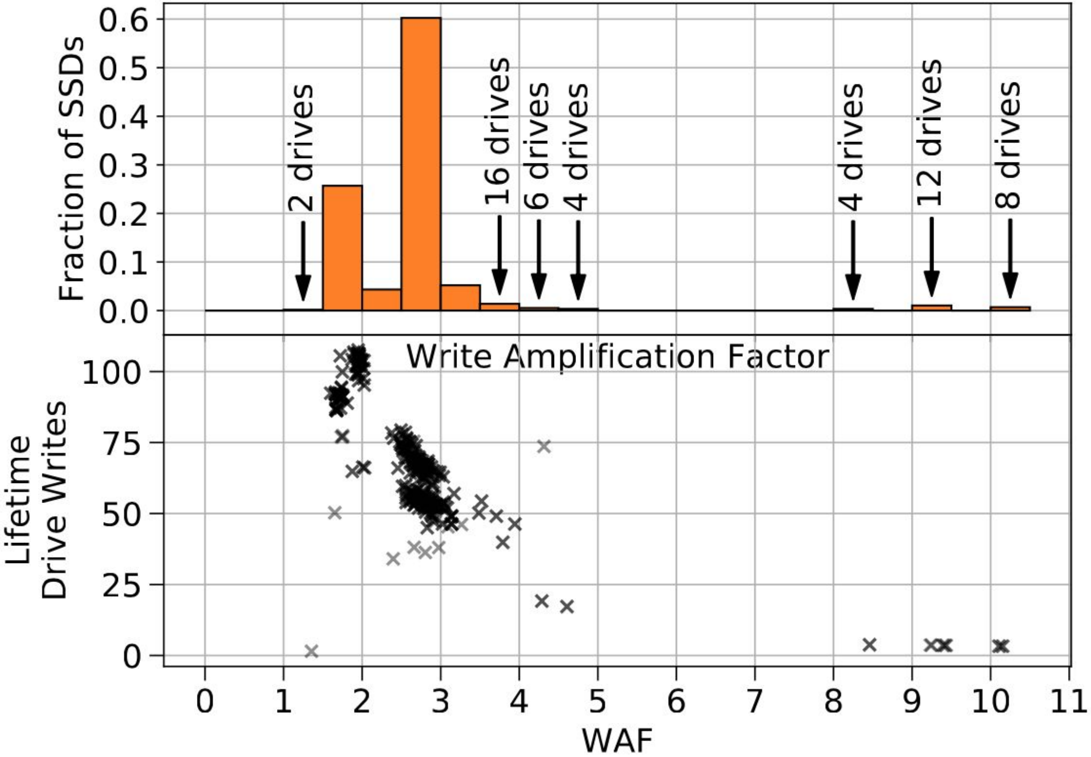
WAF	The Write Amplification Factor (WAF), which results from factors intrinsic to the application workload, accounts for writes that are smaller than a full RAID stripe (read-modify-write) ● This read-modify-write penalty is a function of the anticipated workload
$\left(\frac{D+P}{D}\right)$	Data and Parity blocks need to be accounted for, as a single user write is accompanied by additional parity blocks when written to physical media
$\mathrm{FSWPD}^{\mathrm{ref}}$	File System Writes Per Day (FSWPD) can be derived from Cori directly via telemetry or indirectly from device-level counters ● Lustre file system level data unambiguously shows the user workload in absence of device-level buffering or amplification specific to RAID

Drive Endurance

Figure 2

Distribution of SSD WAFs on the Cori Burst Buffer after ~ 3.4 years in service (top)

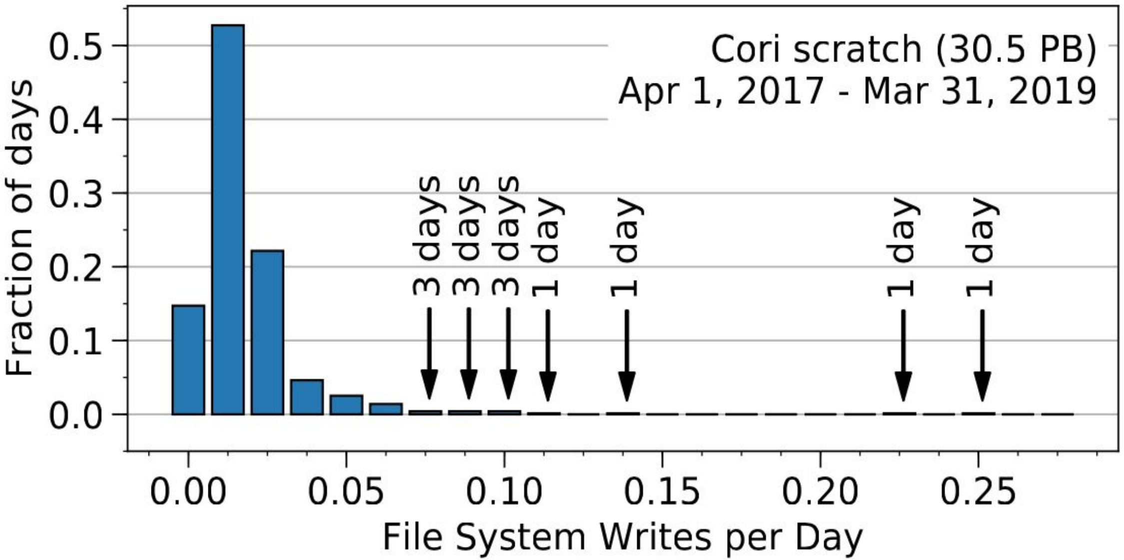
Total lifetime write volumes, normalized to formatted drive capacity, for the WAF distribution (bottom)



Drive Endurance

Figure 3 - Cori scratch write distribution over 2 years, using LMT

- 1 FSWPD = 30.5 PB of writes per day
- Nonzero fractions in the tail are annotated in absolute days
- Long tail of days that experience abnormally high write volumes (scratch being used as a data processing capability)



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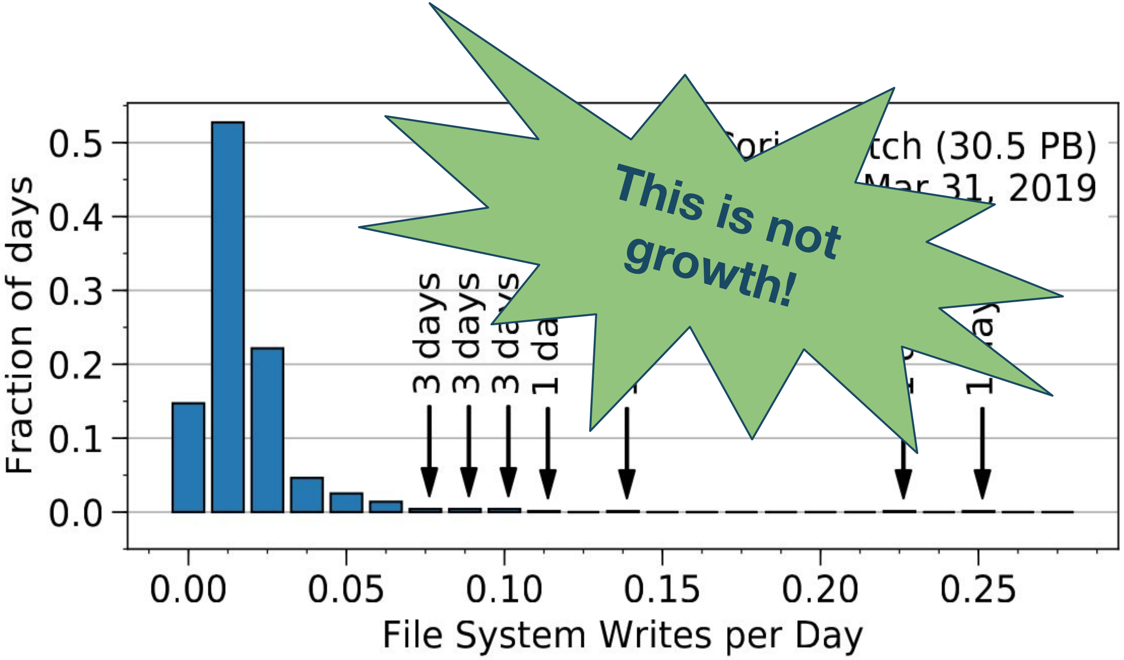


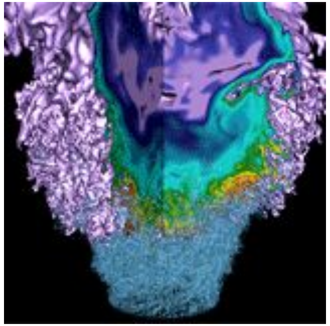
This is not growth!

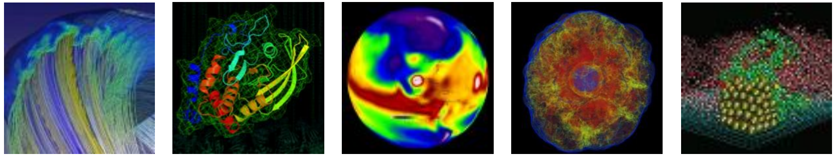
Drive Endurance

- Many HPC deployments utilize extreme-endurance SSDs (**$ $ $ $**)
- NERSC reserves up to 20% of Cori's Burst Buffer SSDs for wear leveling
  - Effectively enduring 10 DWPD
  - Instead of the 3 DWPD as per factory default
  - This endurance is not needed!
- The continually increasing bit density of NAND, allows for larger drives, and an increased DWPD (absolute endurance)
- There is a trade of performance for endurance, since per-SSD performance does not scale with per-SSD capacity
- Looking at file system-level load data and sources of write amplification:

$\mathrm{DWPD}^{\mathrm{new}}$ **1 DWPD leaves significant headroom for the anticipated Perlmutter workload**

Metadata Configuration





Metadata Configuration

- Lustre's Data-on-MDT (DOM) feature allows for a configurable number of bytes of every file to be stored on the same storage devices as their file metadata
- Major benefits are
  - Lock traffic is reduced since data and metadata are colocated
  - File size can be determined without sending RPCs to OSSes
  - Small file I/O interferes much less with large-file I/O on OSTs
- However, DOM adds additional complexity to system design, because MDT capacity must now account for
  - Capacity to store inodes
  - Capacity required to store small files' contents
- **Precise definition of what constitutes "small" is site-configurable**

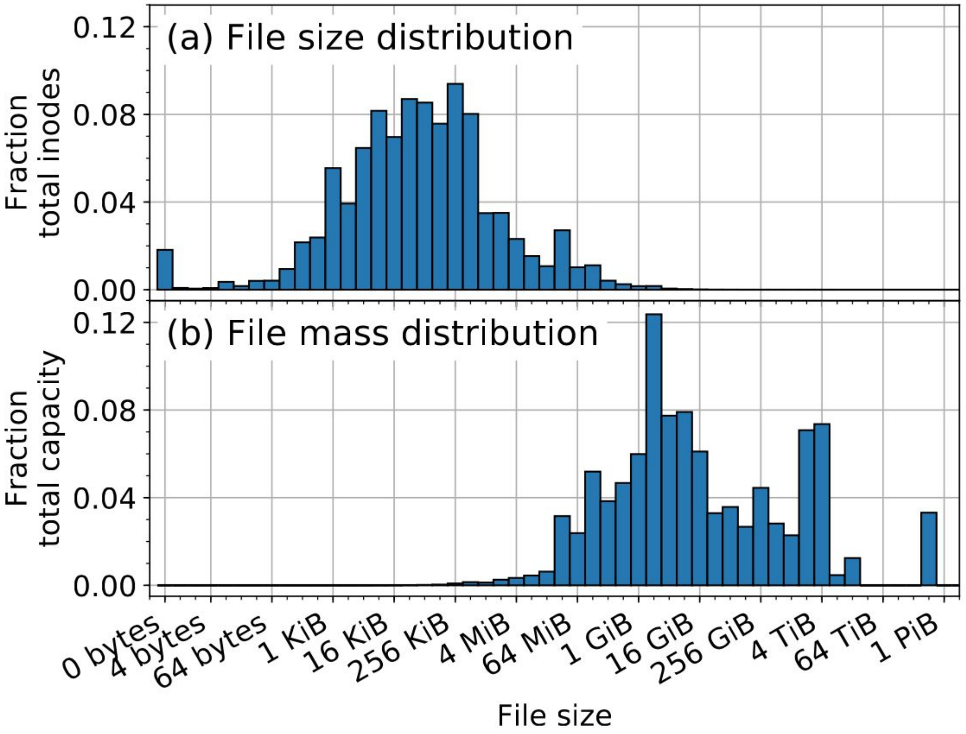
Metadata Configuration

Figure 4 - Probability distribution of file size and file mass on Cori's file system in January 2019

95% of the files comprise only 5% of the capacity used

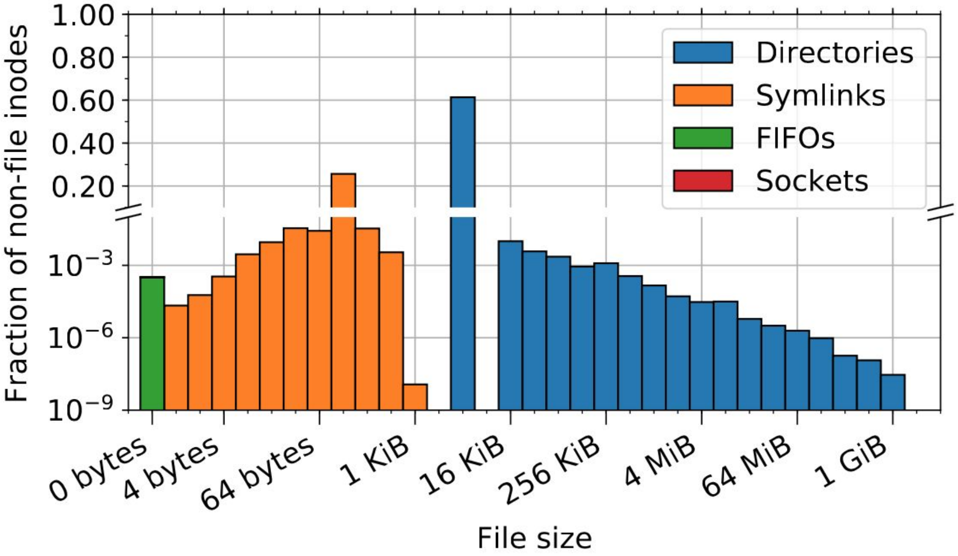
MDT capacity for a new system is a function of the *expected* file size distribution

- Average file size alone is not enough because HPC file size distribution skews towards small files
- Small changes to the mean file size could represent a significant change to where the optimal DOM size threshold should be



Metadata Configuration

Figure 5 - Probability distribution of inode sizes on Cori's file system in January 2019



MDT Capacity Required for Inodes

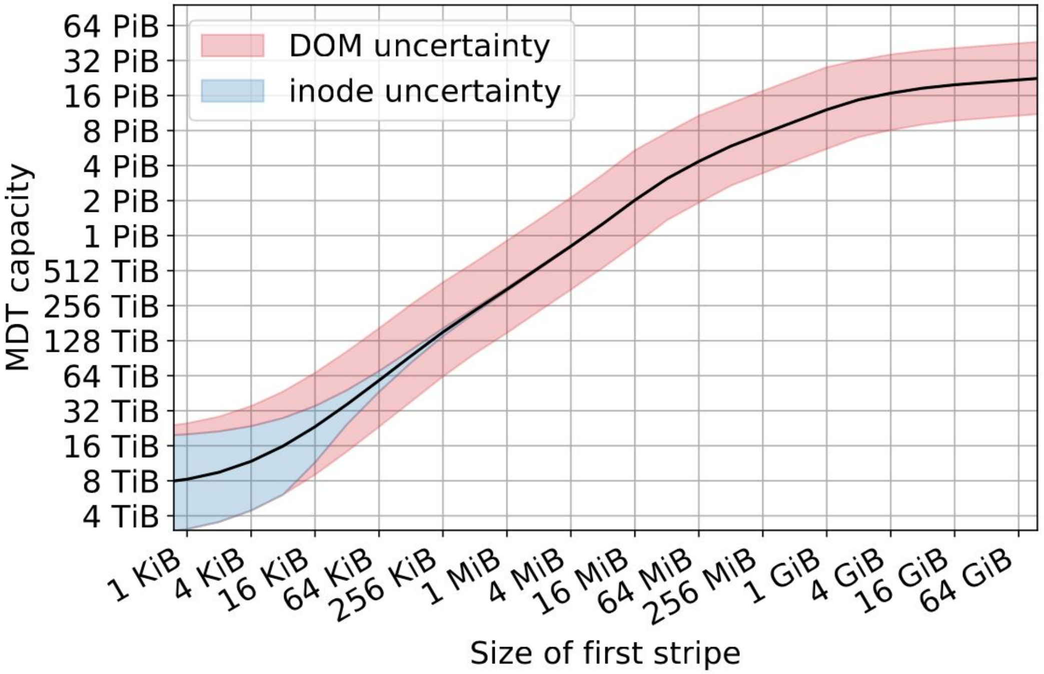
- Lustre reserves 4 KiB of MDT capacity per inode
- BUT Directories with millions of files are significantly larger
- Most extreme case is 1 GiB in size for 8 million child inodes

Metadata Configuration

Figure 6 - Required MDT capacity as a function of DOM threshold

Shaded area bounded by the minimum and maximum estimated requirements dictated by the DOM component and the inode capacity component of MDT capacity

- At a very small DOM threshold, the large number of small files does not consume much MDT space
- At a very large DOM threshold, the great majority of files are stored entirely within the MDT, and only a small number of very large files dictates a higher MDT capacity



Metadata Configuration

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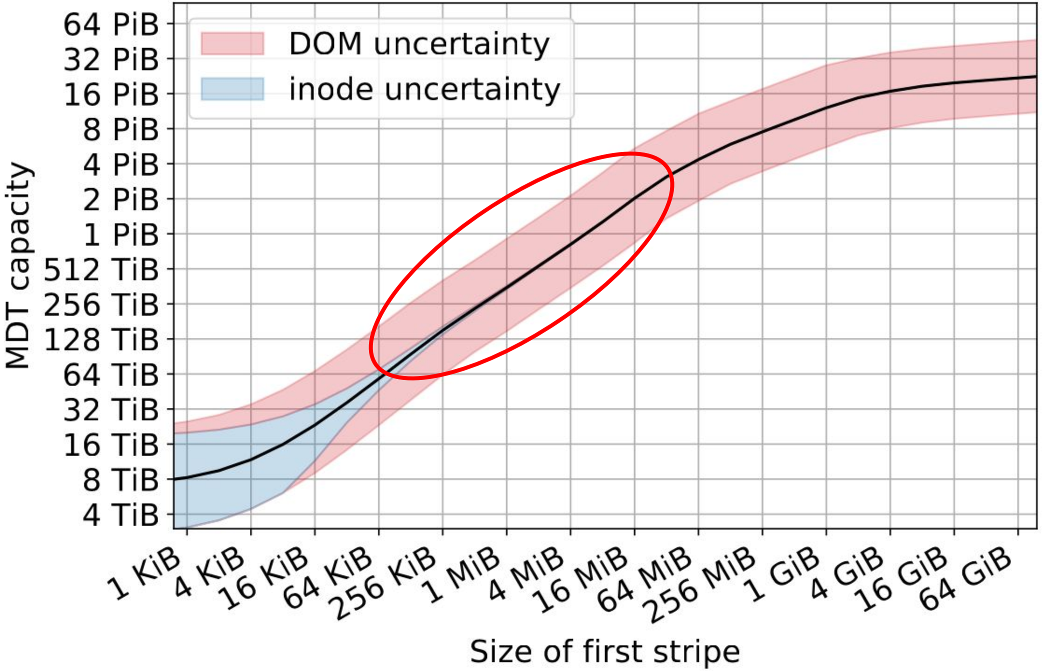

Metadata Configuration

- Assuming the capacity of DOM is proportional to cost and the DOM threshold is proportional to IOPS performance:

Figure 6 becomes a price-performance curve as well!

- In this case, increasing the DOM threshold above several GiB is not an optimal configuration for price/performance
- DOM threshold is inversely proportional to bandwidth performance since DOM is not striped, so choosing a large DOM threshold would have a negative impact on a per-file bandwidth

Conclusion

- Workload data from a reference system can be used to determine the best balance of
  - Cost
  - Performance
  - Usability
- Quantifying the relationship between
  - Purge policy
  - Growth rate
  - File size distribution
  - Design space parameters
    - Data capacity
    - SSD endurance
    - Metadata configuration
- As the economics of flash continue to displace hard disk drives from HPC performance storage tiers, these analytical methods will become increasingly important in future system deployments

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Thank You