Architecture and Performance of the Perlmutter 35 PB All-NVMe Lustre File System at NERSC

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NERSC is the mission computing facility

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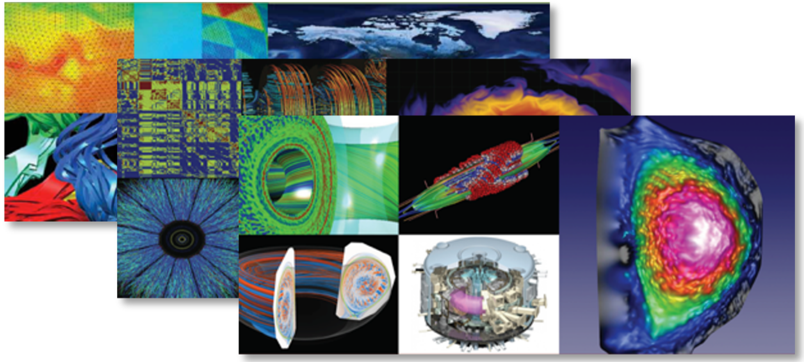
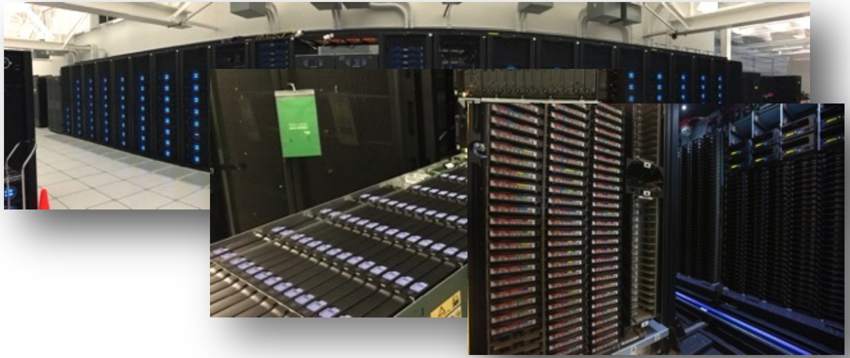




- **Diverse user community**
  - 8,000 active users, 900 projects
  - 700 applications (sim, data, AI)
- **We design for our workload**
  - Many jobs at many scales
    (40% of hours go to capability jobs)
  - Small, incoherent I/O
  - Not just checkpoint/restart!
- **Flash is ideal for versatile performance**

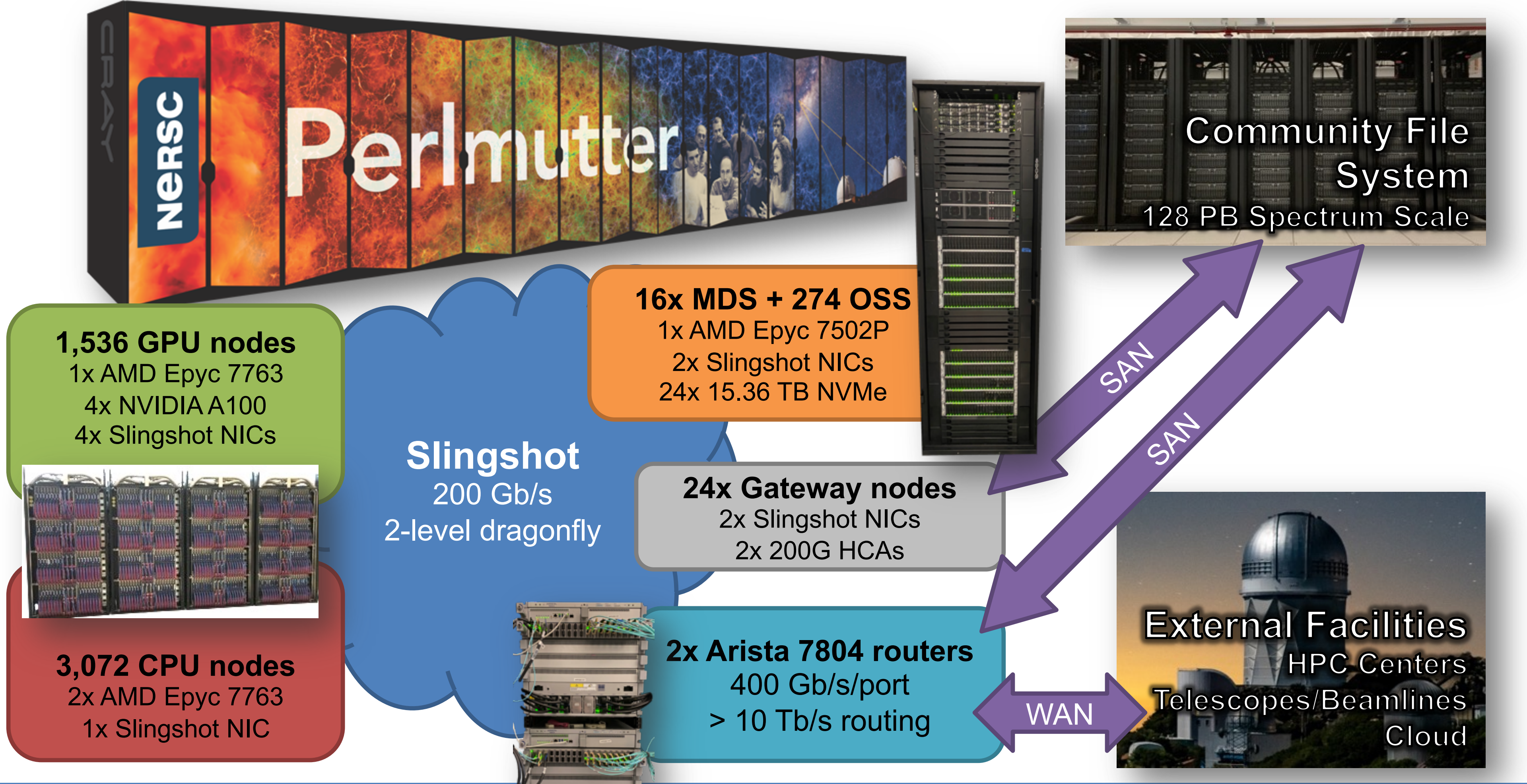
NERSC's first foray into NVMe at scale: Cori (2015)

Cori – Cray XC-40

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

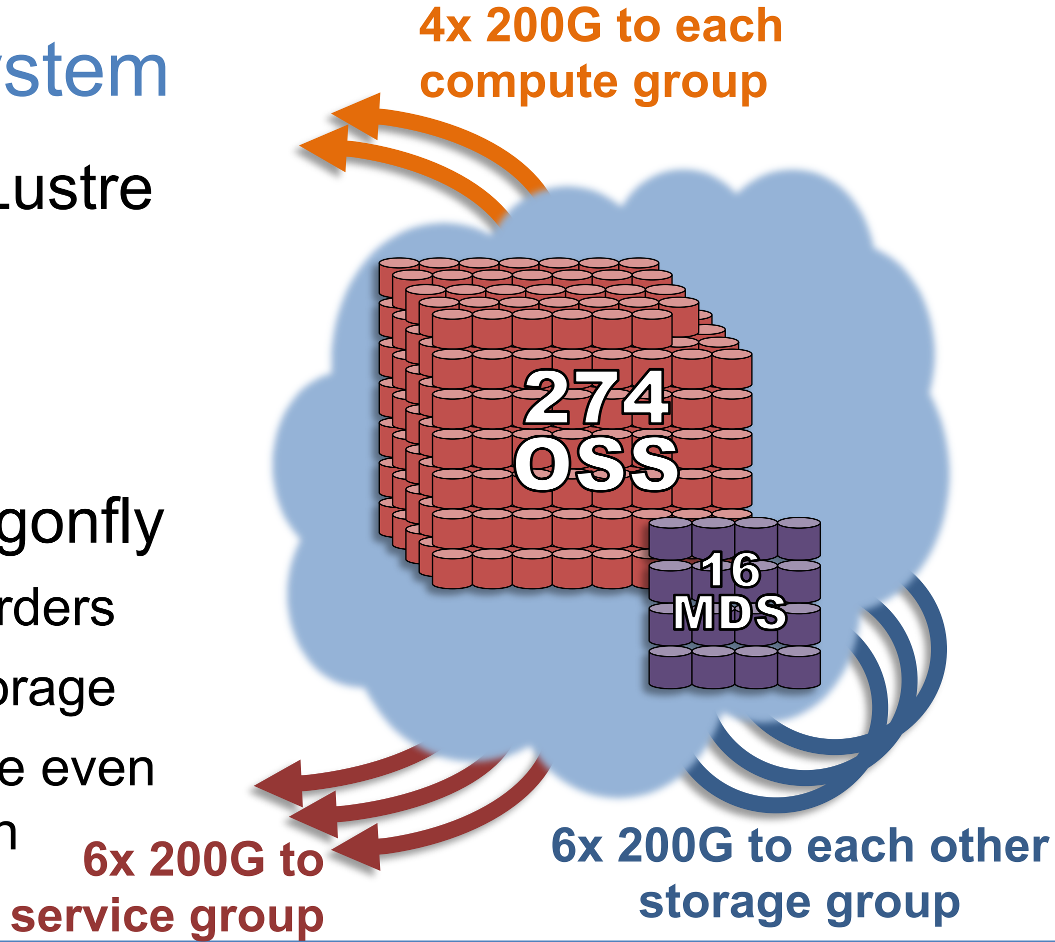
I/O Subsystem

- 1.8 PB, 1.5 TB/s burst buffer
  - DataWarp File System
  - 1,152 NVMe SSDs
  - RAID0
- 30 PB, 700 GB/s scratch
  - Lustre File System
  - 10,168 HDDs
  - 8+2 RAID6

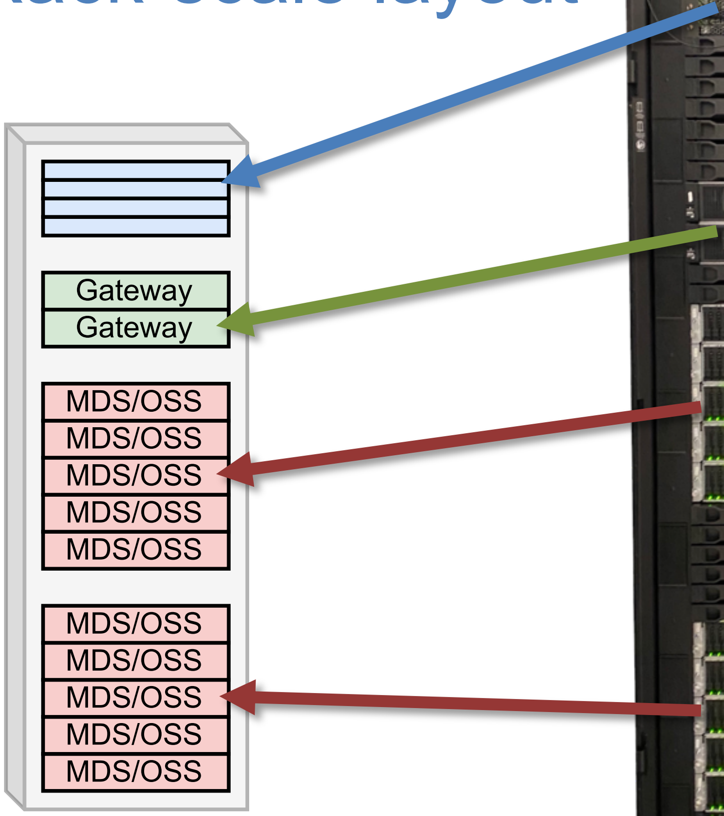

NERSC
Perlmutter
CRAY
Community File System
128 PB Spectrum Scale
16x MDS + 274 OSS
1x AMD Epyc 7502P
2x Slingshot NICs
24x 15.36 TB NVMe
1,536 GPU nodes
1x AMD Epyc 7763
4x NVIDIA A100
4x Slingshot NICs
Slingshot
200 Gb/s
2-level dragonfly
SAN
SAN
24x Gateway nodes
2x Slingshot NICs
2x 200G HCAs
3,072 CPU nodes
2x AMD Epyc 7763
1x Slingshot NIC
2x Arista 7804 routers
400 Gb/s/port
> 10 Tb/s routing
WAN
External Facilities
HPC Centers
Telescopes/Beamlines
Cloud

Perlmutter's I/O Subsystem

- 35 PB usable, all-NVMe Lustre
  - 274x OSSes
  - 16x MDSes
  - 3,480x SSDs total
- Directly integrated on dragonfly
  - No LNet routers or I/O forwarders
  - Four dragonfly groups for storage
  - File system remains available even if compute cabinets are down



Rack-scale layout



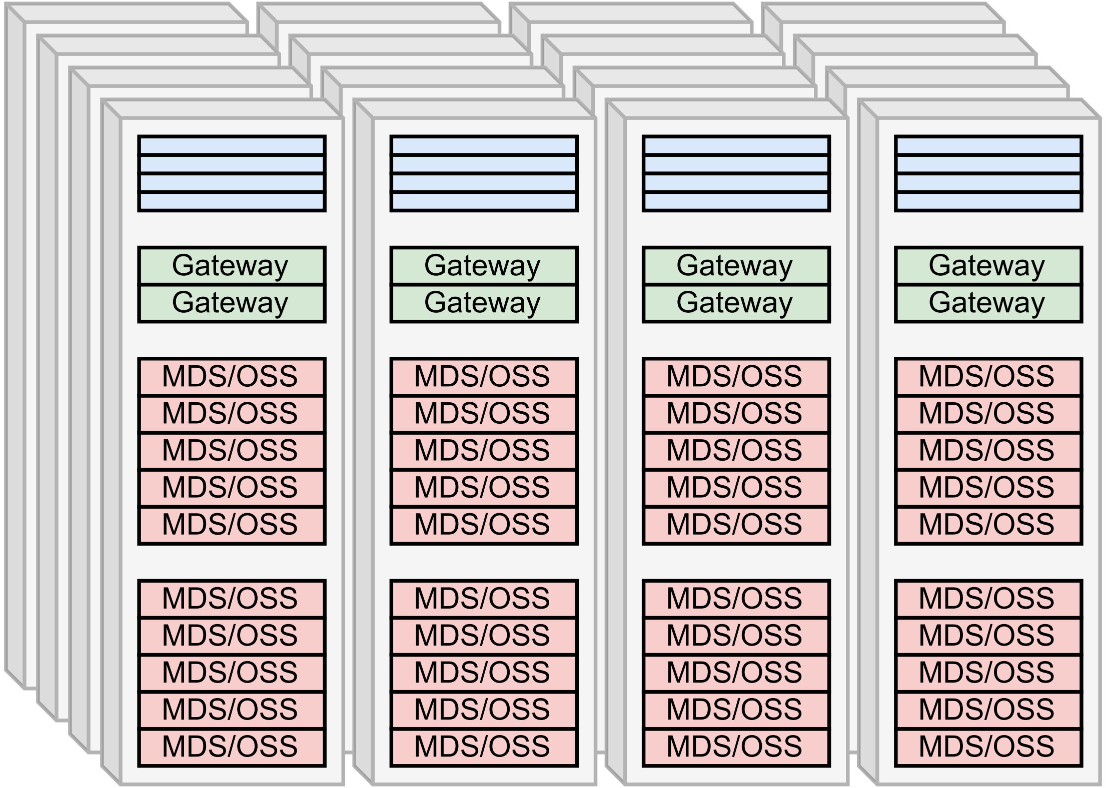
Physically (approx.)

- 10x 2U24 enclosures
- 240x 15.36T NVMe SSD
- 2x gateway nodes – Slingshot to InfiniBand
- Slingshot switch complex

Logically (approx.)

- 20 OSS and/or MDS
- 3.6 PB raw
- 1.6 - 2.7 PB usable

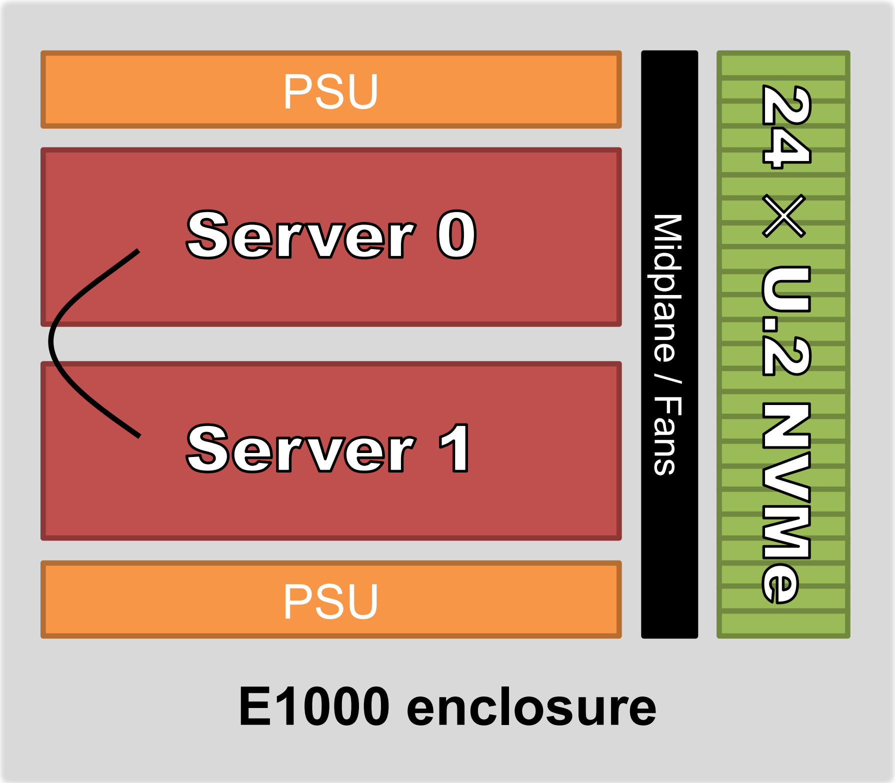
Rack-scale layout



4 racks = 1 group

- Four groups total
- Each connected to every other group in the system
- Compute I/O can get dedicated global links
- 14.4 TB/s/dir to computes

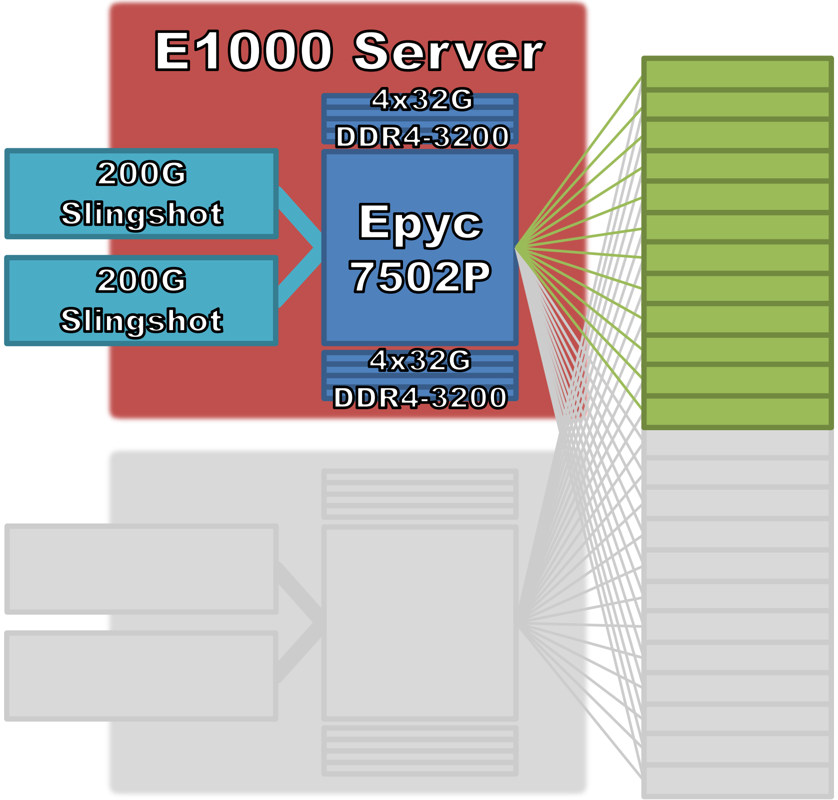
Inside a 2U24 enclosure



Designed for **reliability**

- No single points of failure
  - 2x servers (OSS or MDS)
  - Redundant PSUs, fans, etc
- 24x U.2 15.36 TB NVMe drives
  - Samsung PM1733
  - Dual-ported PCIe Gen4 (2x2)
  - Each server sees 24x drives
- Heartbeating and failover

Servers architected to maximize performance



- Single-socket AMD Rome (128x PCIe Gen4 lanes)
  - Allows switchless design
  - 48 lanes for 24x NVMes
  - 32 lanes for 2x NICs
- One server = one OST/MDT
- One OST/MDT = 12x NVMe
- GridRAID + ldiskfs to maximize performance
  - OST = 8 + 2 + 1 RAID6
  - MDT = 11-way RAID10

Performance efficiency – GridRAID and ldiskfs

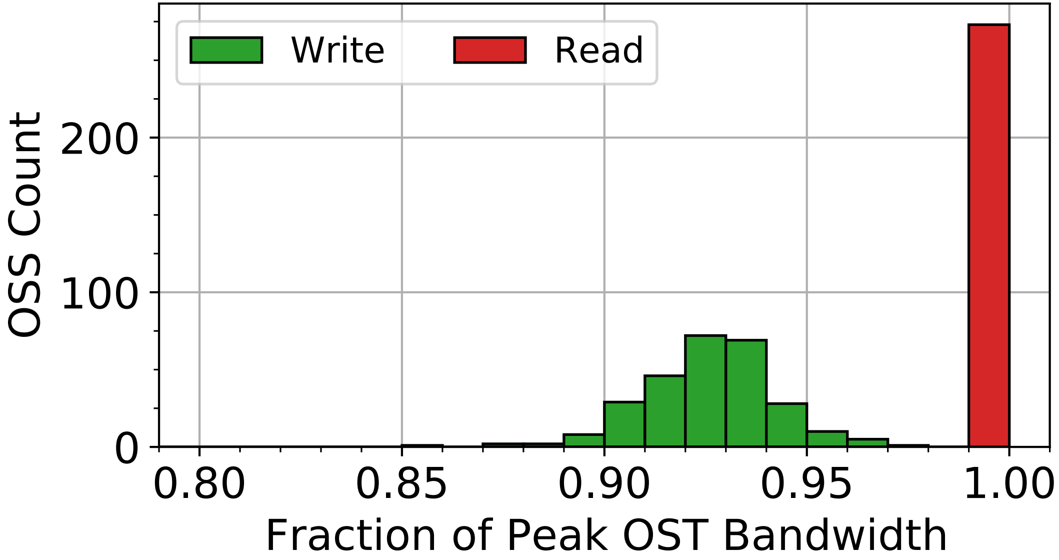
SSD spec sheet

- 3.2 GB/s write
- 3.5 GB/s read

obdfilter-survey

- Writes: 92.6% of peak
  ~3.0 GB/s/SSD
- Reads: 99.9% of peak
  ~3.5 GB/s/SSD

obdfilter-survey results



GridRAID + ldiskfs efficiently delivers NVMe bandwidth

Performance efficiency – Slingshot and LNet

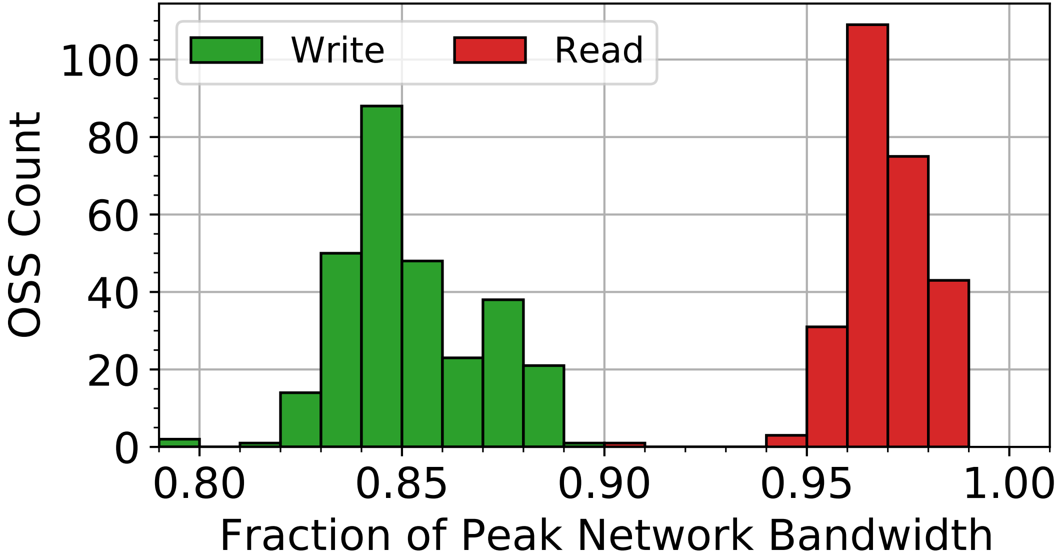
Line rate for NICs

- 2x 200 Gb Slingshot
- 50 GB/s line rate

LNet self-test

- Writes: 84.8% of peak
  ~42 GB/s/OSS
- Reads: 97.0% of peak
  ~48 GB/s/OSS

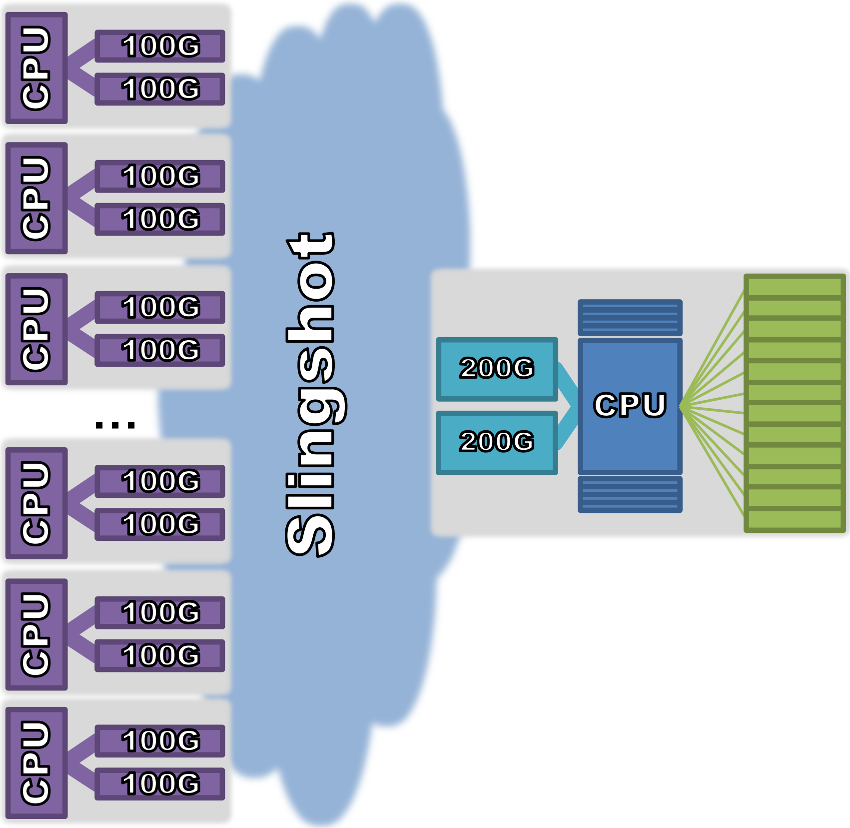
LNet self-test results



Slingshot and LNet multi-rail also efficiently delivers bandwidth

Performance capability of one NVMe OSS

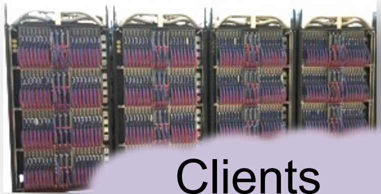
- **Bandwidth**
  - Writes: 27 GB/s/OSS
  - Reads: 41 GB/s/OSS
- **IOPS**
  - Writes: 29 kIOPS/OSS
  - Reads: 1,400 kIOPS/OSS
- **Configuration**
  - 20 to 250 clients
  - 1 OSS, 1 OST (12 NVMes)
  - Slingshot interconnect

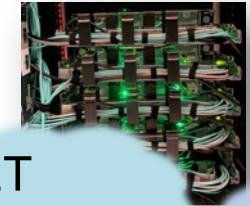


Using Lusre 2.12.4+cray

Reminder: Perlmutter has 274 OSSes

Perlmutter file system: excellent performance efficiency





Clients
(Slingshot)
IOR

41 GB/s read
27 GB/s write
1400 kIOPS read
29 kIOPS write

LNET
(Slingshot)
LNET Selftest

48 GB/s read
42 GB/s write

RAID
(GridRAID)
OBDFilter Survey

43 GB/s read
31 GB/s write

NVMe
(PM1733)
fio

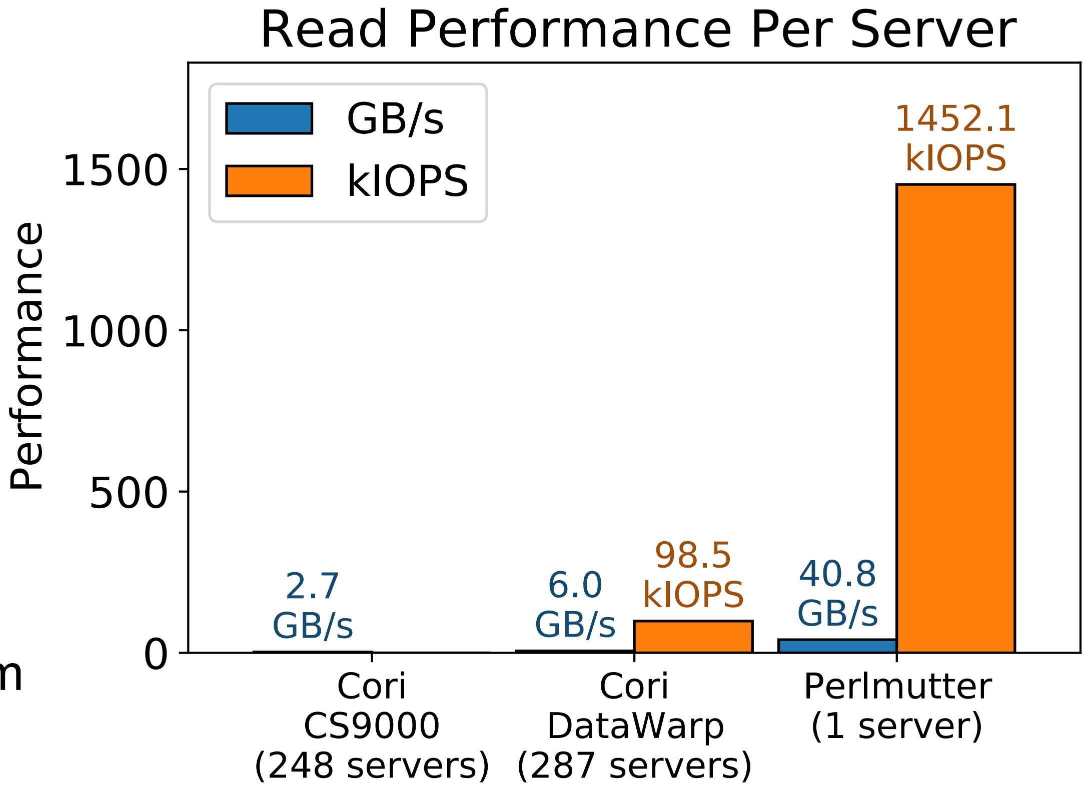
42 GB/s read
38 GB/s write
9,600 kIOPS read
1,600 kIOPS write

88.4%(w) / 97.2%(r) NVMe block bandwidth (remember: 8+2 on writes)

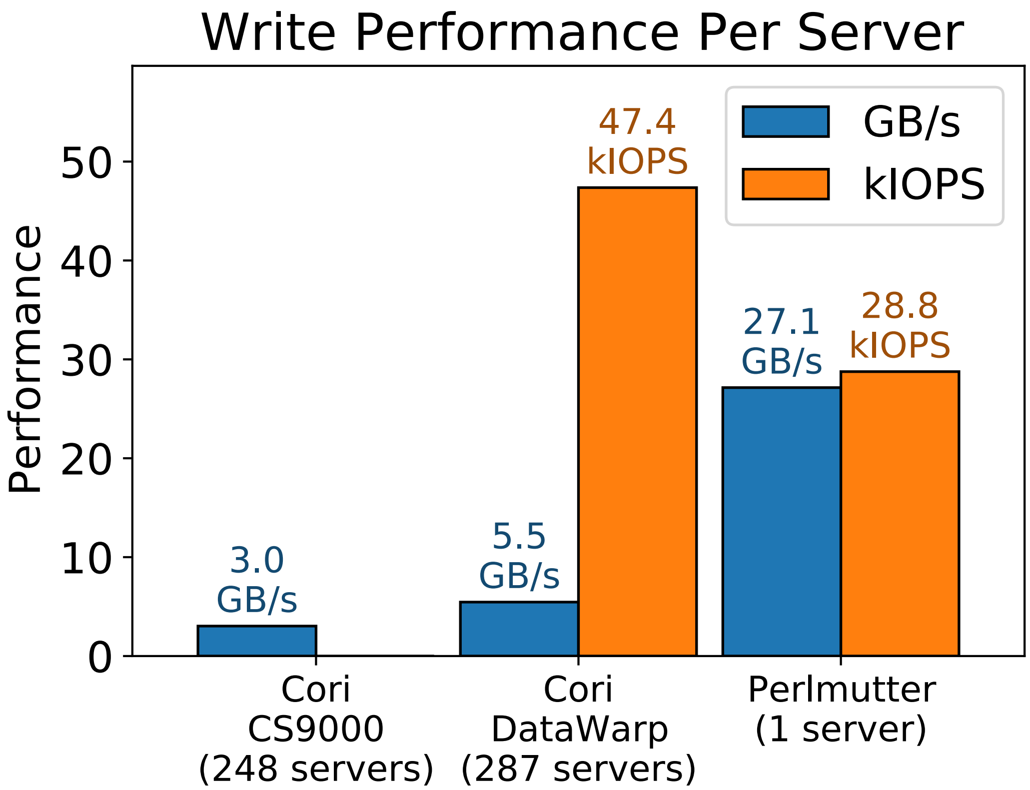
5.33%(w) / 15.1%(r) NVMe block IOPS (after read-modify-write penalty)

How does this compare to Cori for *reads*?

- *NOTE: Perlmutter data does not reflect network scaling*
- **Read bandwidth** up to 15x previous generation
- **Read IOPS** are promising for user experience
  - NERSC is read-heavy
  - Expecting much better interactive responsiveness
  - Expecting less variation from contention



How does this compare to Cori for *writes*?

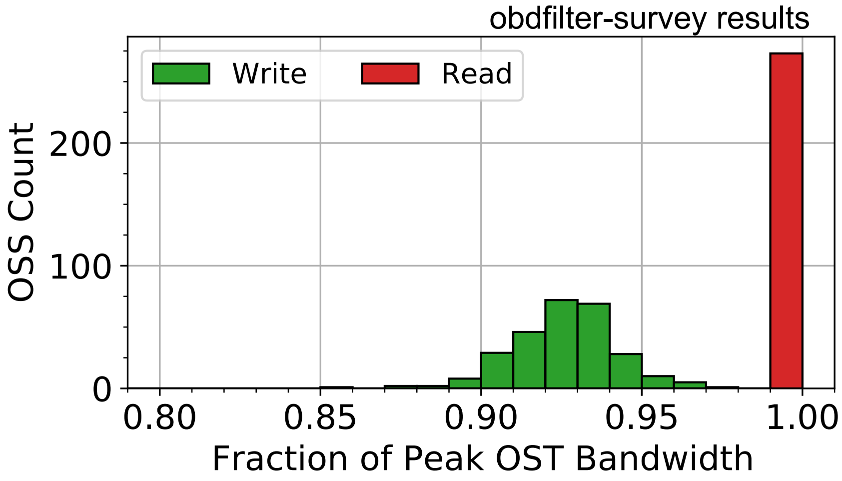


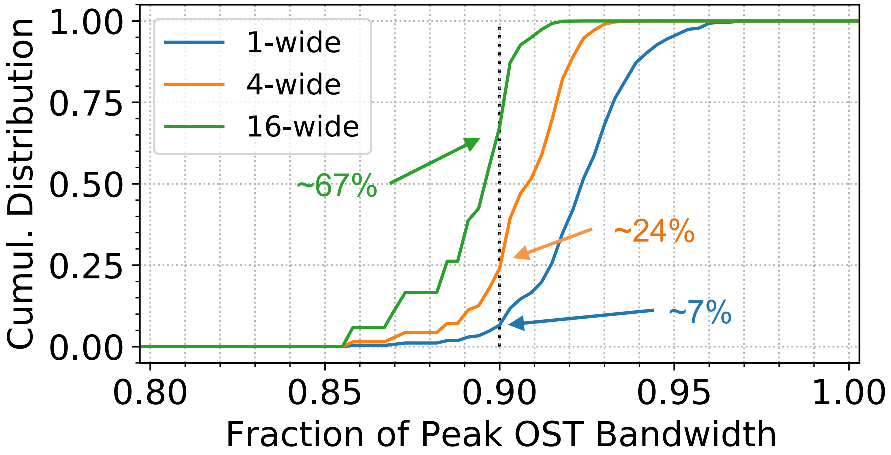
- *NOTE: Perlmutter data does not reflect network scaling*
- **Write bandwidth** is 5x to 9x higher than Cori
- **Write IOPS** falls short of DataWarp
  - RAID6 vs RAID0
  - Perlmutter traded IOPS for resilience

A few surprises so far…

Read and write bandwidths differ

- Reads faster than writes
  - write parity overhead
  - NVMe is faster on reads
- Writes *vary* more
- Must balance
  - stripe width (high bandwidth)
  - write variability (straggling OSTs)

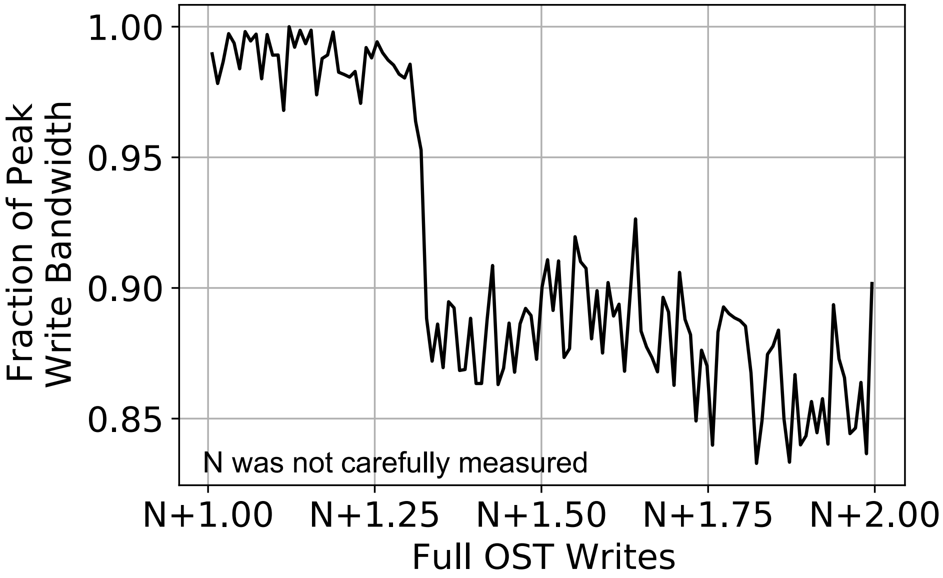




A few surprises so far…

SSD OSTs slow with age

- analogous to HDD fragmentation
- ~10% write bandwidth lost after ~5 full OST writes
- fstrim completely restores write performance!
- NERSC anticipates monthly trim
  - 5x OSTs = 665 TB
  - expect 2.2 PB – 2.9 PB/day
  - 5x OST writes = 60 - 80 days



Take-aways and next steps

- Perlmutter's 35 PB all-NVMe file system is built on HPE Cray E1000
- Lustre, GridRAID, ldiskfs, Slingshot, and LNet multi-rail efficiently deliver bandwidth *and* IOPS from NVMe to clients
- More scale results to follow!
  - Scaled up to O(1,000) compute nodes and 274 OSSes already!
  - Metadata/DNE testing kicking off
  - Optimal striping, PFL, etc for users also being examined

Thank you!

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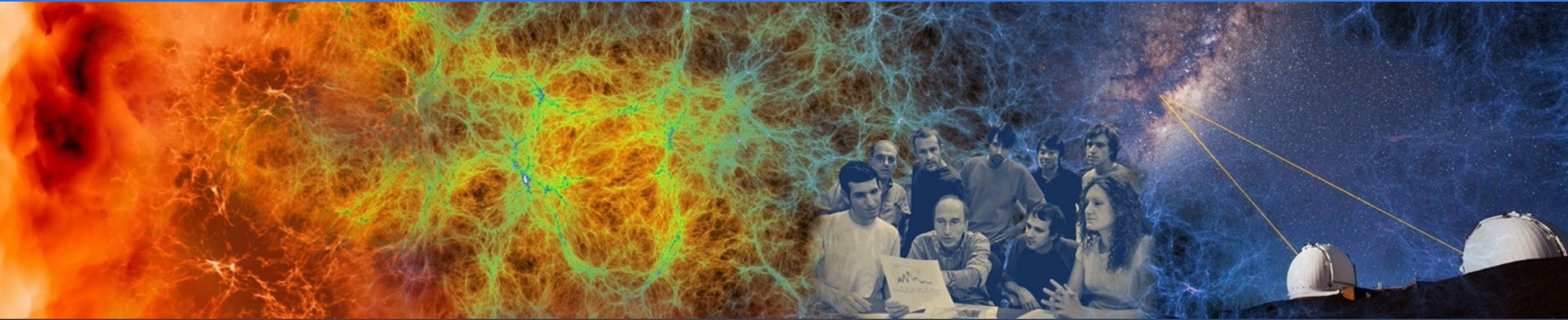

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