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The Limits of ZFS Redundancy

Hunting for Bottlenecks in ZFS Failure Recovery using NVMe Drives

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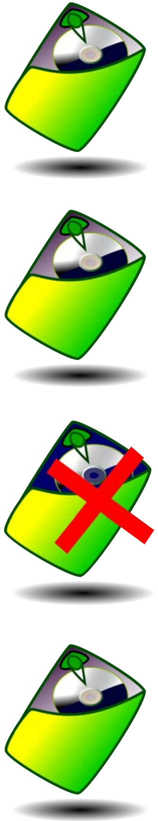
Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Background: Redundancy and Performance

- Data redundancy is important
  - Disks failure scales linearly with quantity
  - Data is important; takes time to compute (snapshotting)
- ZFS filesystem implements redundancy in software
  - Often is a “backbone” to other distributed filesystems
- Challenges to data redundancy
  - Resilver operations are costly, especially with capacious disks
  - HDDs are slow
    - Data recovery time depends on disk bandwidth (bottleneck)
- NVMe SSDs: Ideally eliminate disk bandwidth as a bottleneck
  - So… is there still a bottleneck?
- **Goal: Find bottlenecks in ZFS resilver performance**

Method: Testing ZFS Resilver Times in Different Scenarios

1. Create RAIDZ1 zpool (`zpool create ...`)
2. Set desired ZFS-related tunables
3. Take one drive offline, forcing drive fault (`zpool offline -f ...`)
4. Format offlined drive (`nvme format /dev/nvme1n1`)
5. Optional: start I/O load with fio
6. Re-online drive (`zpool online ...`)
7. Initiate resilver by replacing drive (`zpool replace ...`)
8. Gather CPU/RAM/disk metrics until resilver completes
    a. sar, pidstat, iostat
9. Clean up (fio remnants, background processes)
10. Store data
11. Go to step 2



Values: The Baseline

What to measure:

- Time to resilver
- Amount of data resilvered
- Disk utilization
- CPU & Memory usage

Important constants:

- Zpool filled to 60%
- 9x 1.5T NVMe SSDs
- Record size: 1M

Values: The Baseline

What to measure:

- Time to resilver/rebuild
- Amount of data resilvered/rebuilt
- Disk utilization
- CPU & Memory usage

No background I/O load

Important constants:

- Zpool filled to 60%
- 10x 1.5T NVMe SSDs
- Record size: 1M
- Zpool type: RAIDZ1

What to vary:

- Resilver type
  - Sequential, legacy
- Tunables related to resilver
  - zfs_resilver_min_time_ms
  - zfs_vdev_max_active
  - zfs_vdev_async_write_max_active

Values: Simulated I/O Workloads

What to measure:

- Time to resilver/rebuild
- Amount of data resilvered/rebuilt
- Disk utilization
- CPU & Memory usage

I/O load variations:

- 1M sequential read
  - Varying read behaviors
- 1M sequential write
- 4K random read / write
- 1M mix (20% read / 80% write)

Important constants:

- Zpool filled to 60%
- 10x 1.5T NVMe SSDs
- Record size: 1M

What to vary:

- Zpool type
  - RAIDZ, dRAID
- Resilver type
  - Sequential, legacy
- Tunables related to resilver
  - zfs_resilver_min_time_ms
  - zfs_vdev_max_active
  - zfs_vdev_async_write_max_active

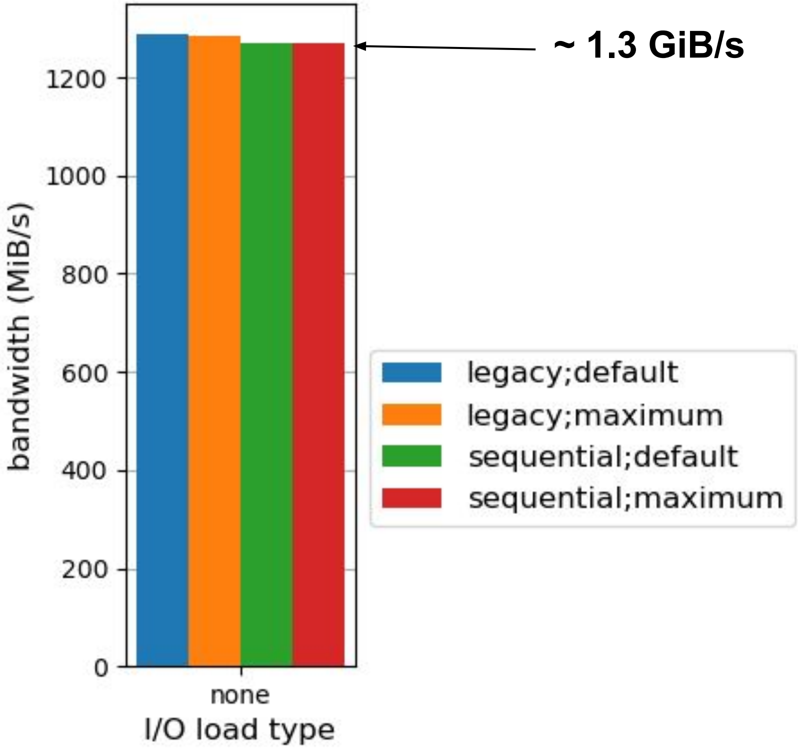
Data Analysis

Disk Benchmarks

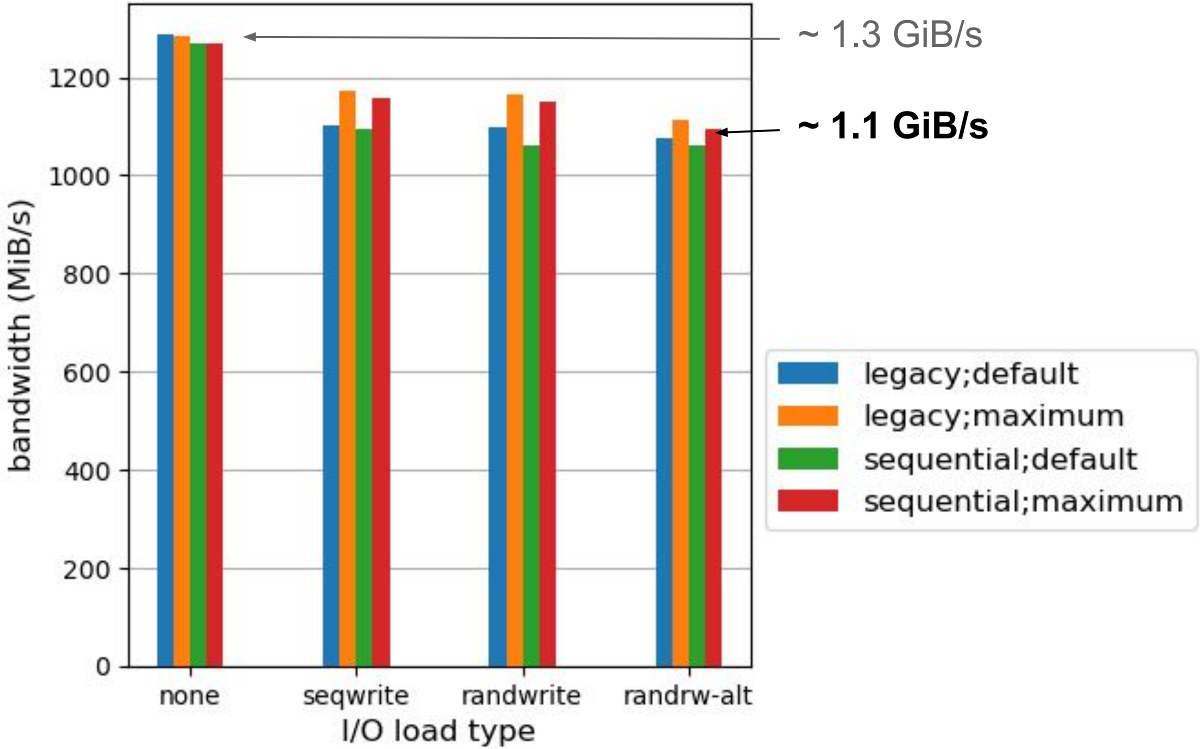
- **Best:** sequential read (~3.5 GiB/s)
- **Worst:** random read/write (~710 MiB/s)

		Multiple Test (loops=5, 1M seq, 4K rand, numjobs=32, iodepth=16)								
		Drive								
		nvme0n1	nvme1n1	nvme2n1	nvme3n1	nvme4n1	nvme5n1	nvme6n1	nvme7n1	nvme8n1
Seq Read	Avg IOPS	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414
	Avg BW (MiB/s)	3,414.50	3,414.74	3,414.77	3,414.66	3,414.78	3,414.71	3,414.33	3,414.05	3,414.88
Seq Write	Avg IOPS	1,794	1,905	1,842	1,841	1,820	1,838	1,802	1,812	1,798
	Avg BW (MiB/s)	1,794.96	1,905.59	1,842.38	1,841.07	1,820.68	1,838.67	1,802.65	1,812.40	1,798.20
Rand Read	Avg IOPS	697,216	691,372	690,914	689,801	695,298	694,390	681,698	690,185	685,381
	Avg BW (MiB/s)	2,723.50	2,700.67	2,698.88	2,694.54	2,716.01	2,712.46	2,662.88	2,696.04	2,677.27
Rand Write	Avg IOPS	373,978	428,880	376,811	374,890	373,143	375,793	373,826	373,955	373,015
	Avg BW (MiB/s)	1,460.85	1,675.31	1,471.92	1,464.42	1,457.59	1,467.94	1,460.26	1,460.76	1,457.09
Rand Read/Write	Avg IOPS R/W	182,210/ 182,135	190,788/ 190,709	182,732/ 182,656	182,657/ 182,581	182,175/ 182,099	183,416/ 183,340	182,651/ 182,576	182,081/ 182,006	182,038/ 181,963
	Avg BW (MiB/s) R/W	711.76/ 711.46	745.27/ 744.96	713.80/ 713.50	713.50/ 713.21	711.62/ 711.33	716.47/ 716.17	713.48/ 713.19	711.26/ 710.96	711.09/ 710.79

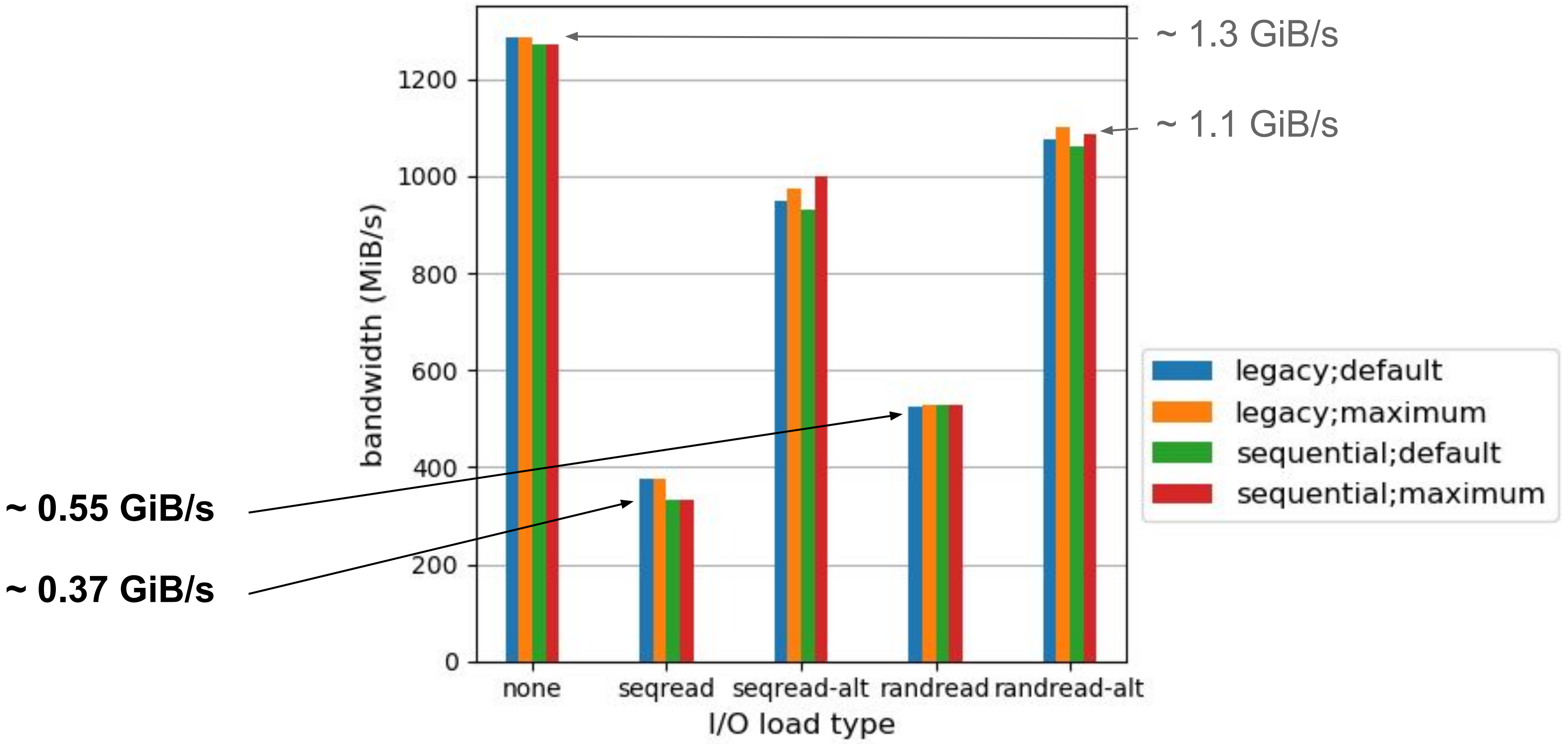
Reported Average Resilver Bandwidths: Baseline



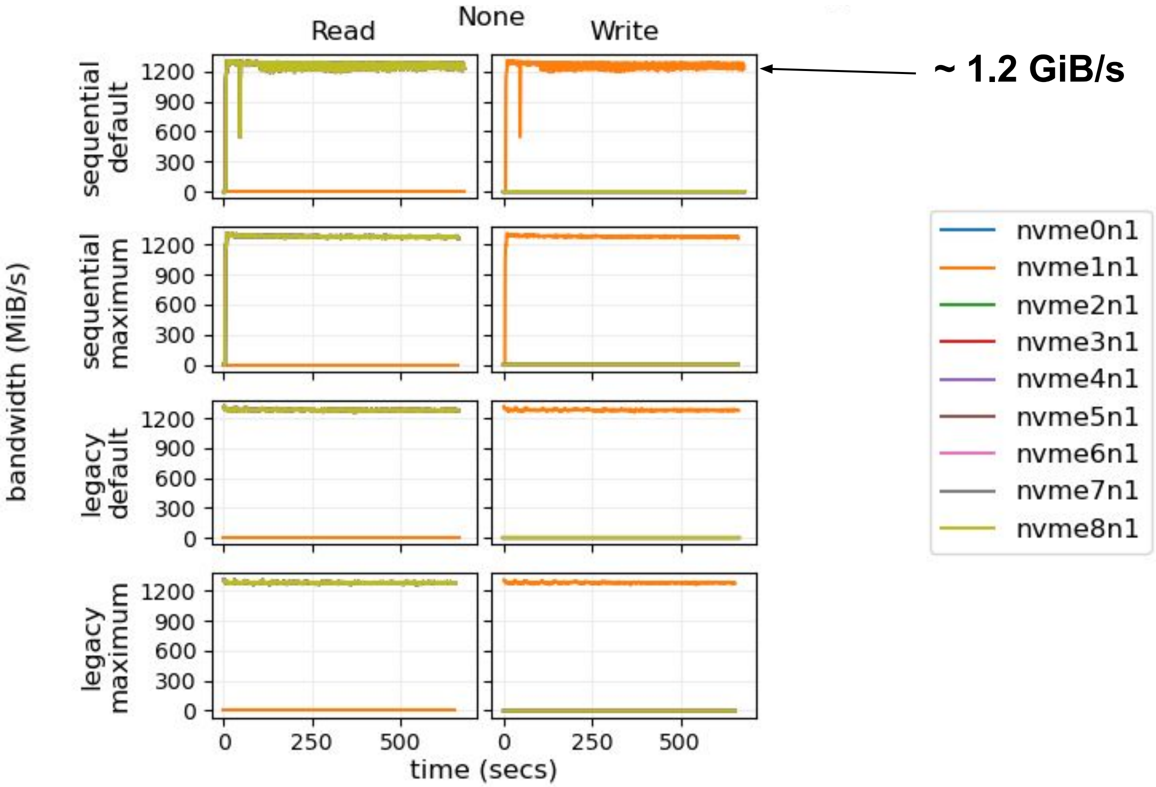
Reported Average Resilver Bandwidths: Write I/O



Reported Average Resilver Bandwidths: Read I/O

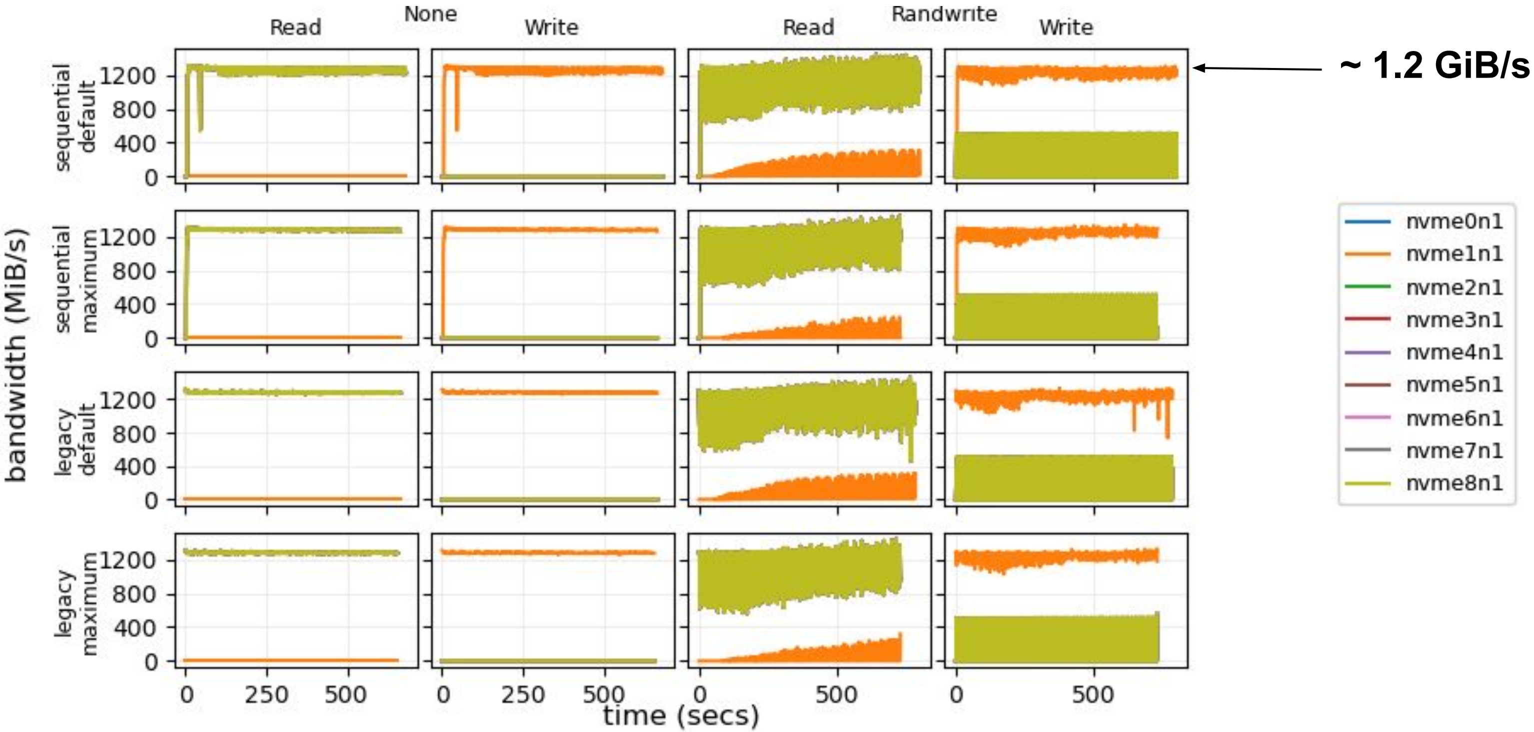


Reported Disk Bandwidths: Baseline



Measured ZFS Resilver (write): ~1.3 GiB/s

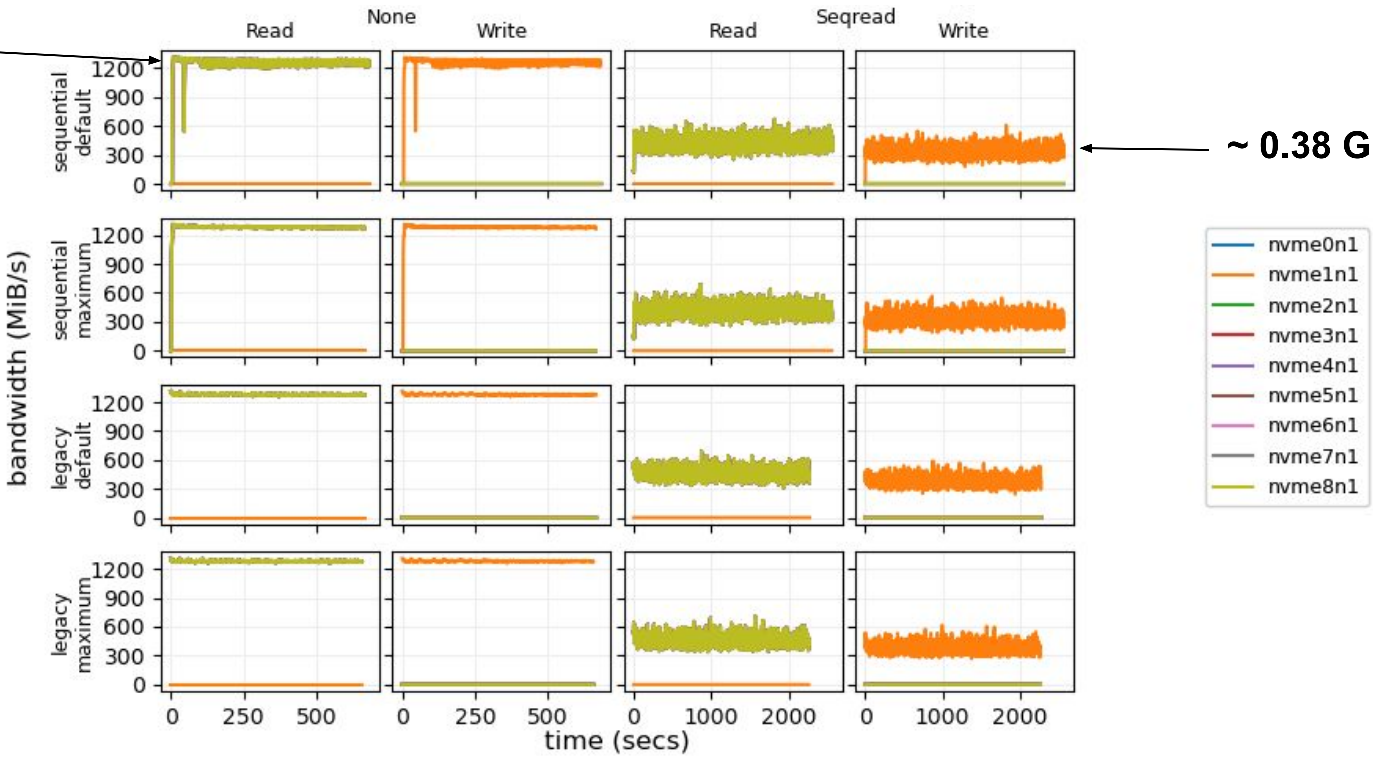
Reported Disk Bandwidths: Write I/O



Disk Write Benchmark: ~ 1.5 GiB/s

Reported Disk Bandwidths: Seq Read I/O

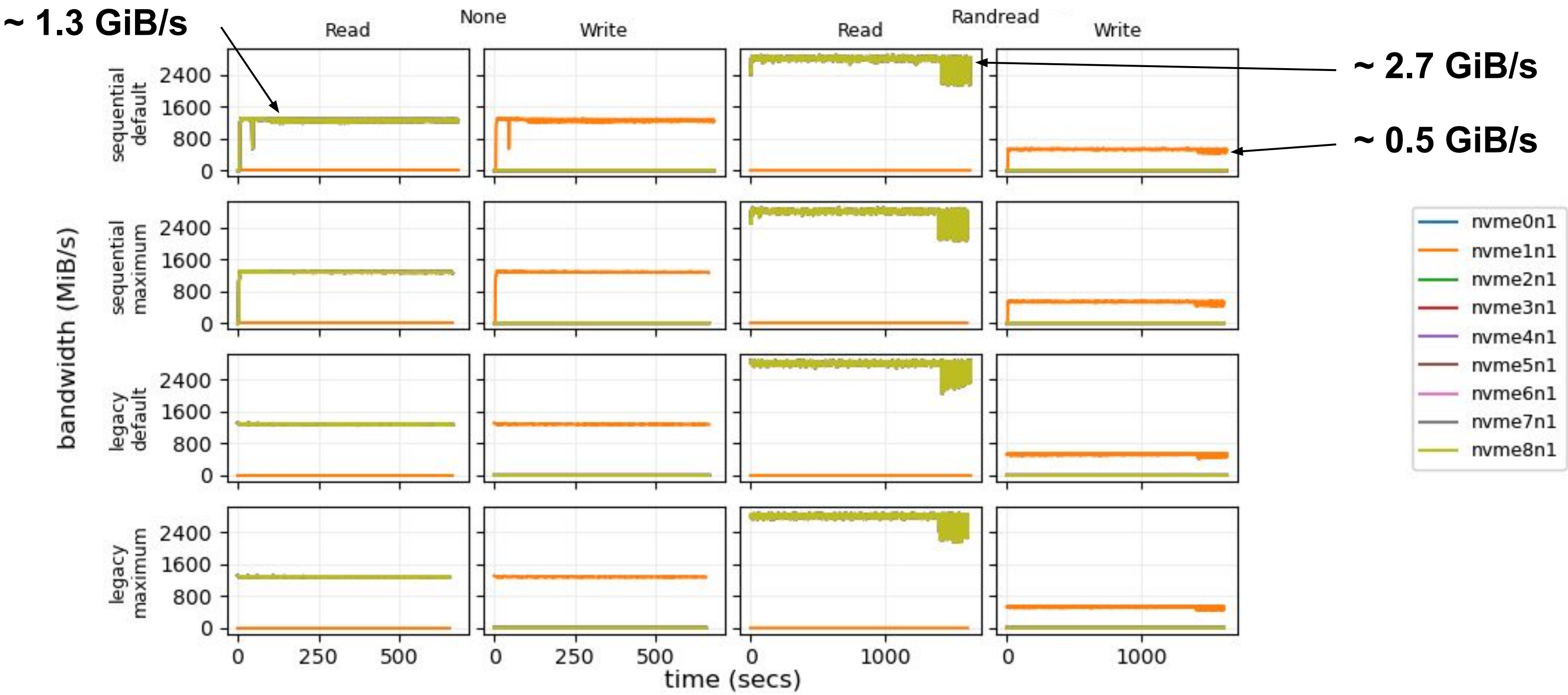
~ 1.3 GiB/s



~ 0.38 GiB/s

Disk Seq Read Benchmark: ~ 3.4 GiB/s

Reported Disk Bandwidths: Rand Read I/O



Disk Rand Read Benchmark: ~ 2.7 GiB/s

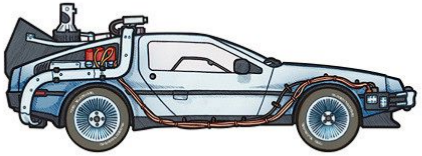
What can we conclude?

Interpreting the Data

- No I/O load: drives still do not reach benchmarked values
  - Resilver read bandwidth limited by write bandwidth of replaced drive
  - Presence of mixed I/O types (read/write) per disk
- Given these workloads: varying tunables/resilver does not vary resilver time by much
- **Bottleneck** in RAIDZ: dependence on write bandwidth of replaced drive
  - Still a reasonable performance target (minor bottleneck)
- **Bottleneck** in ZFS resilver during read workload
  - Reading un-resilvered data interferes with resilver
    - Mechanism yet to be explored

Looking Ahead

- What about dRAID?
  - Issues during resilver tests (kernel panic during rebuild)
  - Explore rebuild/reprotect operations
- Improving ZFS behavior in certain scenarios
  - Read-during-resilver mechanism
- Run more tests for more variation with the same workloads
  - Eliminate possible outlier data
- Compare to ZFS mirror performance
  - Parity vs. copy



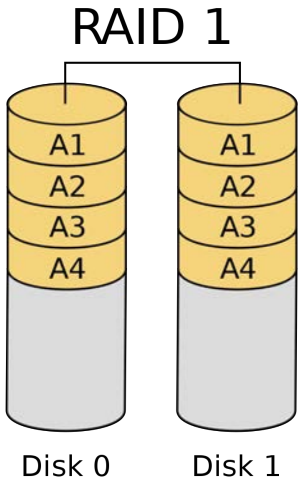
Questions?

Backup Slides

Background

What is Redundancy?

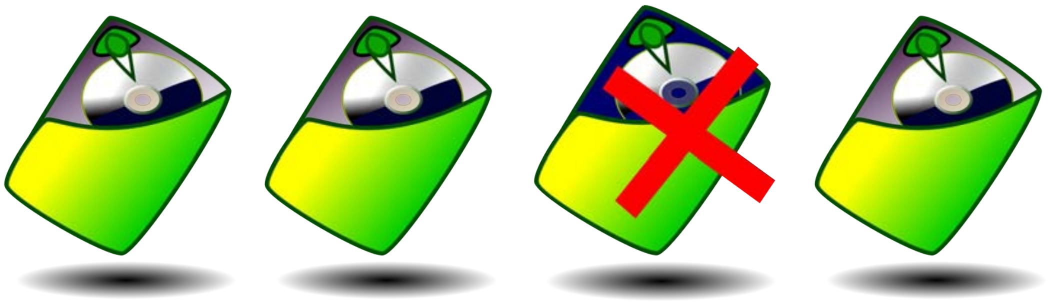
- Storage: The presence of extra information
  - Used to reconstruct existing information after a failure
  - Erasure codes
  - Can be full data copies or parity
- Examples
  - ECC Memory
  - Erasure codes
  - RAID
  - ZFS



Source: Wikimedia Commons https://upload.wikimedia.org/wikipedia/commons/thumb/b/b7/RAID_1.svg/800px-RAID_1.svg.png

Why Redundancy?

- Disks fail.
  - Many disks = high probability of failure
- Data is important.
  - Most tasks are mission critical
- Data can take time to compute.
  - E.g., time-intensive simulations



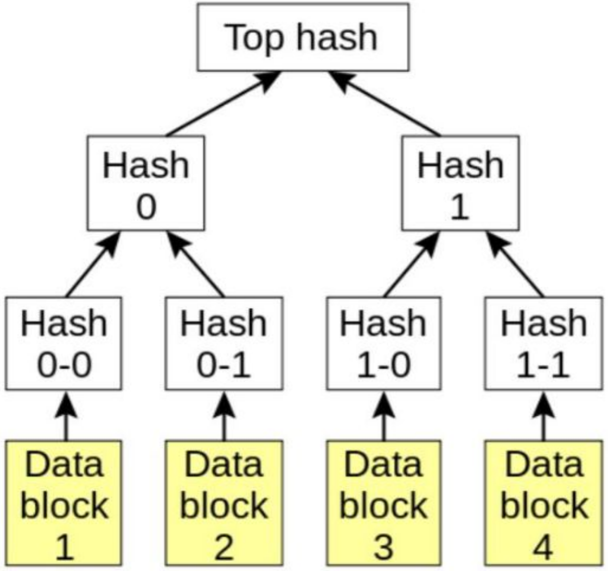
Common Implementation: ZFS

ZFS: Filesystem/Logical Volume Manager

- Allows redundancy in software
  - RAIDZ
  - dRAID
  - Mirroring
- Often is a “backbone” to other distributed filesystems
  - Lustre OSTs, MDTs
- Open source
- “Resilver”/“rebuild” operations for RAIDz/dRAID
  - How do these operations affect I/O performance?

ZFS: Relevant Terminology

- **Scrub**
  - traverse block pointers, comparing checksum to existing one
- **Resilver**
  - Reconstruct data by traversing block pointers
  - Scrub data during operation
  - Two types: sequential and legacy
- **RAIDZ**
  - RAID-like zpool configuration
    - 1, 2, or 3 parity units
  - Parity not limited to single disk



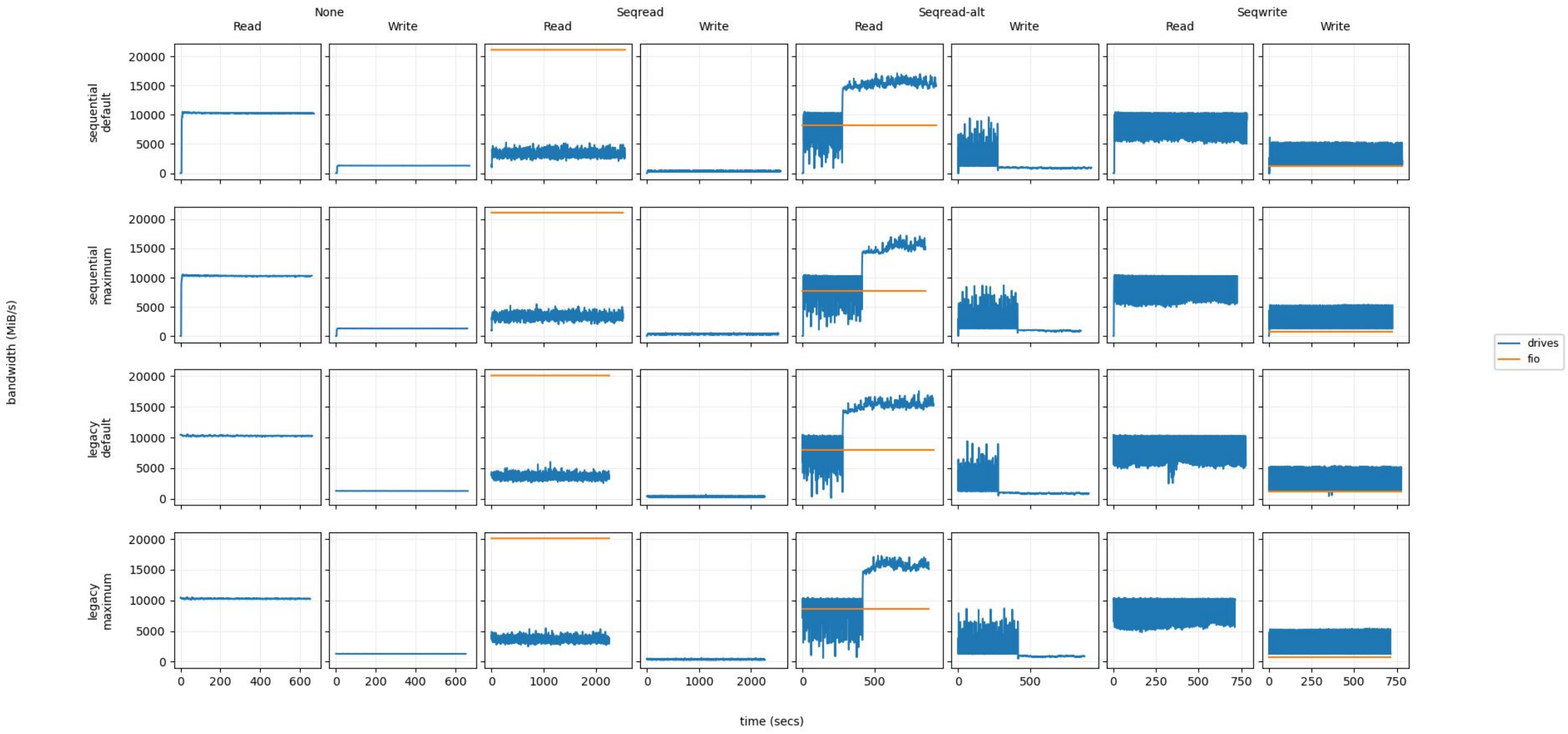
Challenges With ZFS

- Resilver operations are costly
  - Parity calculation involves many I/Os
- Conventional HDDs are slow...
  - Data recovery can take a long time
  - Disk bandwidth is a significant bottleneck for data recovery
- NVMe SSD drives are fast!
  - Ideally eliminates disk bandwidth as a bottleneck
  - So… is there still a bottleneck?
    - How can we find out?

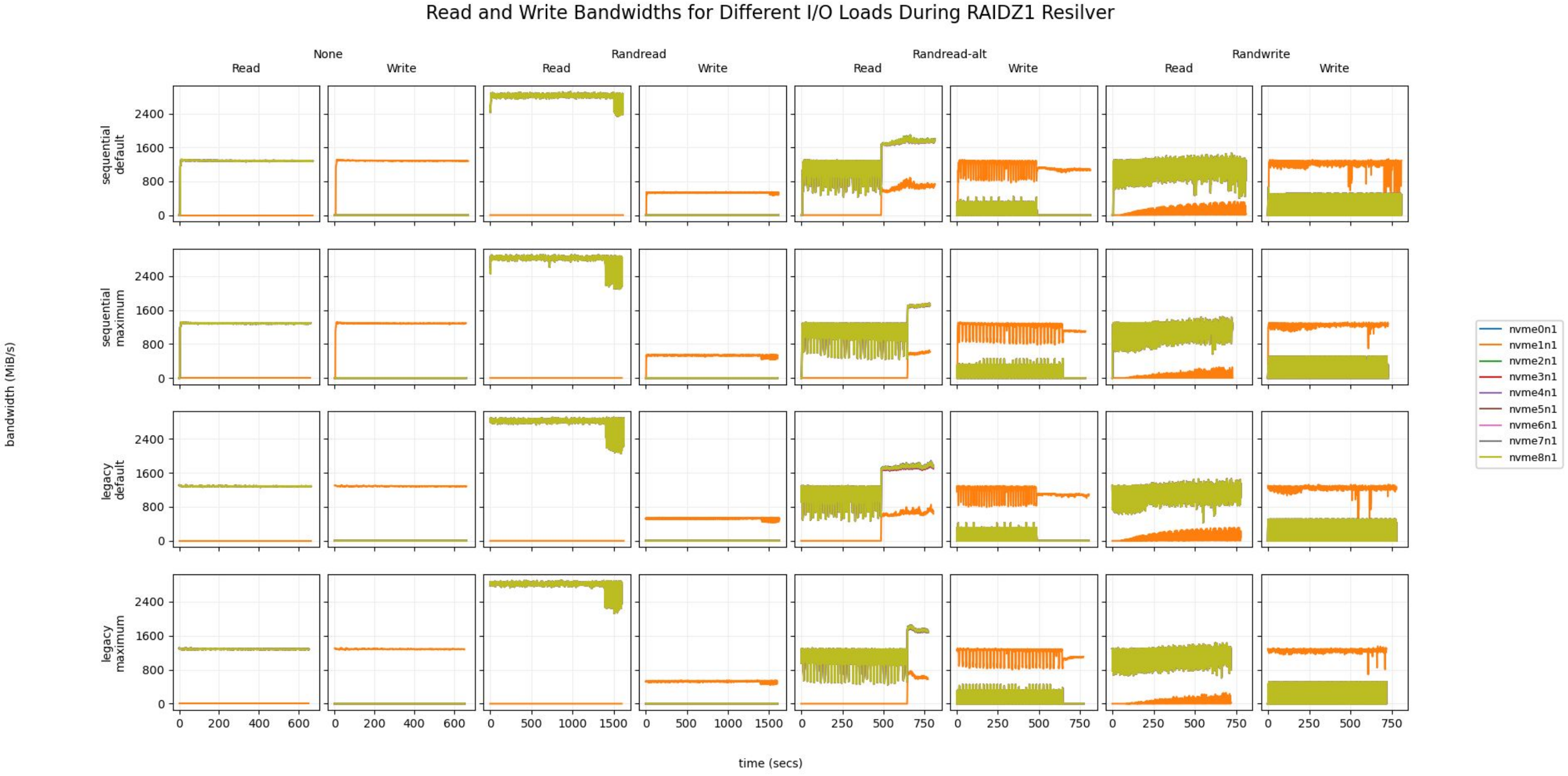
Goal: Find bottlenecks in ZFS rebuild/resilver performance!

The Setup

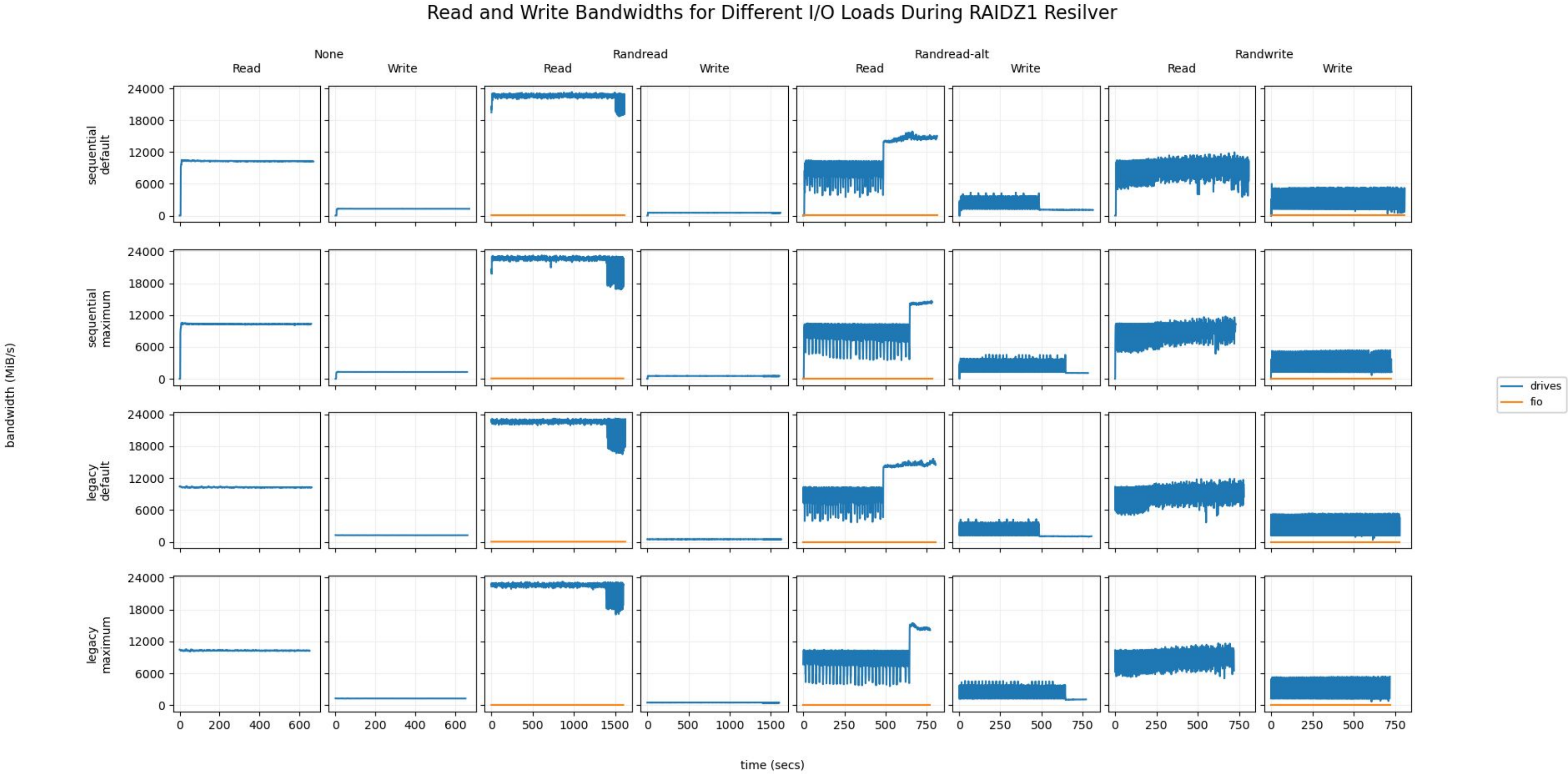
Reported Aggregate Disk Bandwidths (Sequential)



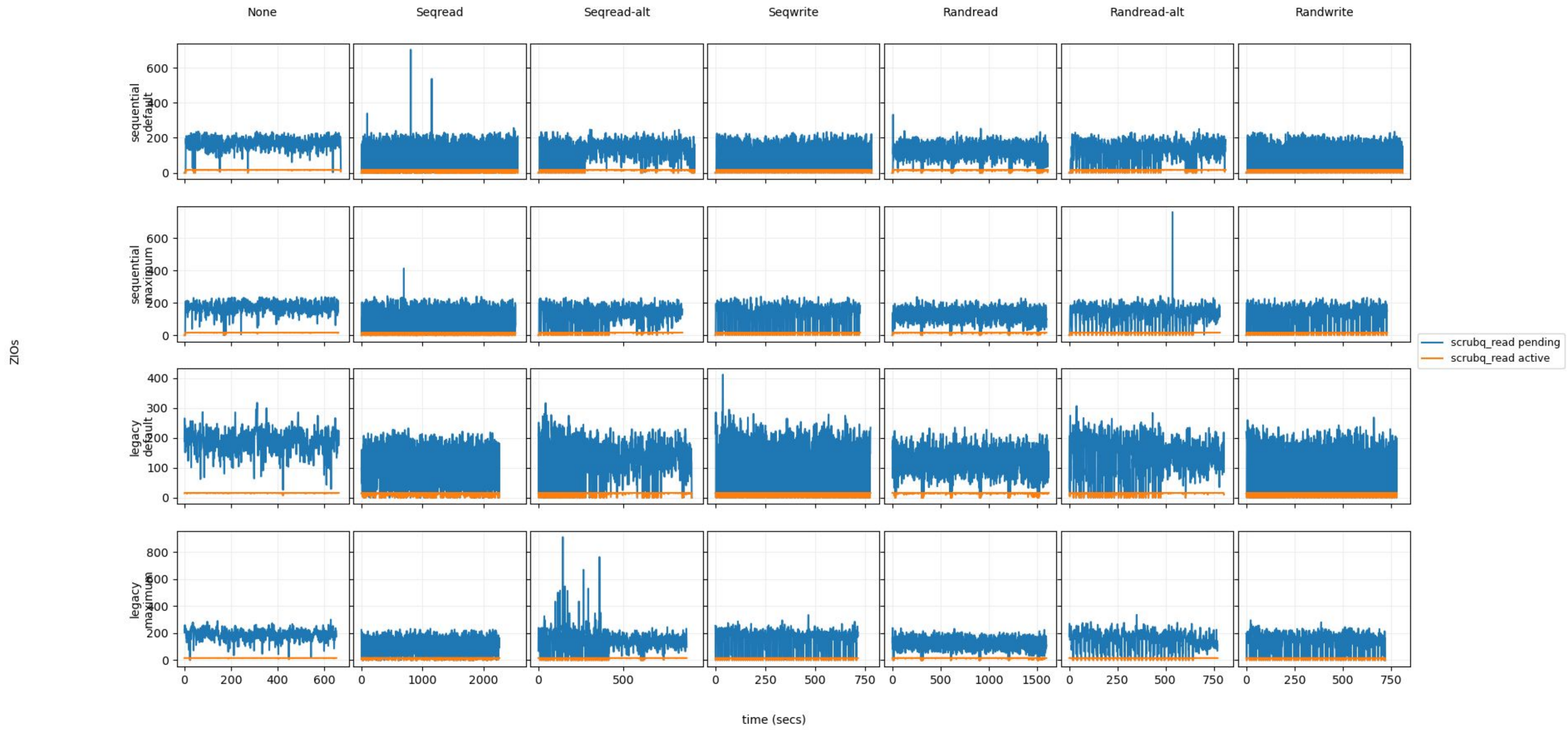
Reported Disk Bandwidths (Random)



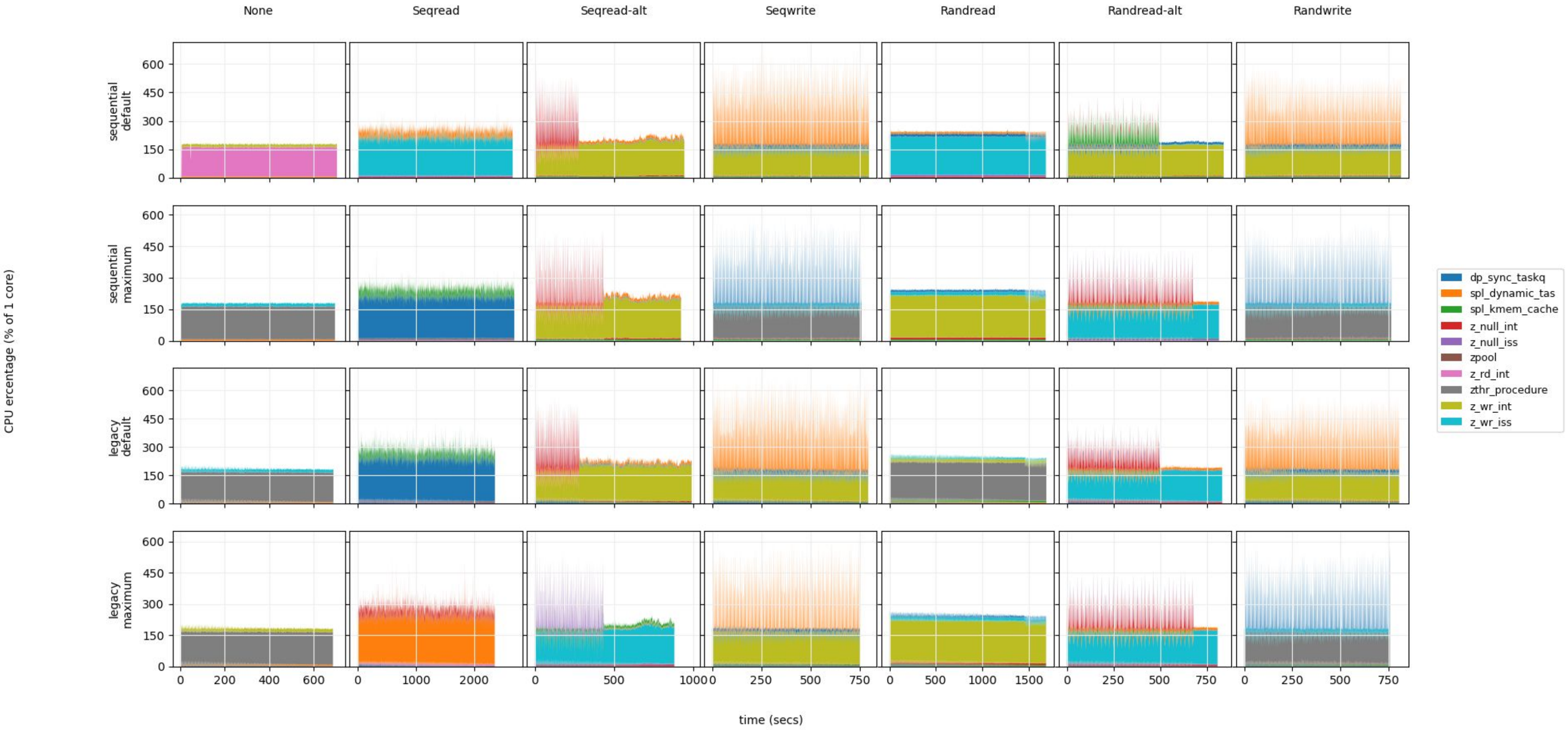
Reported Aggregate Disk Bandwidths (Random)



Scrub Queue Depths



CPU Usage by ZFS



Interpreting the Data

- Continually reading unresilvered data is a worst case.
  - Exact ZFS mechanism yet to be studied
- Even with no I/O load, the drives do not reach benchmarked values.
  - Most likely due to mixed I/O types
- Varying scrub tunables and resilver type does not vary resilver time by much.
- Baseline cases: not at NVME per drive performance
  - Still a reasonable performance target (no major bottleneck)