ECSE-4320 Project 3 Lab Report

NVMe Benchmarking & Storage Performance Characterization

Test Environment

- Device partition: `/dev/nvme0n1p7` (fresh filesystem, mounted at `/mnt/nvme0n1p7`)
- Tool: `fio 3.36` with `ioengine=libaio`, `direct=1`, time-based 30s runs, 10G working set
- Parser / visualization: `parse_results.py` (custom) + generated plots in `plots/`
- Raw per-job fio outputs now stored under `results/raw/` (cleaned workspace); aggregated log at `results/FIO_Benchmark.txt`.
- Initial run used a composite multi-job file (`nvme_test.fio`) with `group_reporting` causing a single aggregated stats block; subsequent isolated executions (via `run_missing_jobs.sh`) populate per-job data.

Goals (Per Project Spec)

1. Zero-queue (QD=1) baselines (4K random & 128K sequential, read & write, avg/p95/p99)
2. Block size sweep (4K→256K) for random & sequential
3. Read/Write mix sweep (4K random, 100R / 70R / 50R / 0R)
4. Queue depth sweep (≥5 points, 4K random) to form throughput vs latency curve
5. Tail latency characterization (p50/p95/p99/p99.9) at mid-QD and near knee

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Zero-Queue Baselines (Current Captured Data)

These results are generated into `baseline_table.md` and reproduced here.

Workload	Avg Lat (µs)	p50 (µs)	p95 (µs)	p99 (µs)	IOPS	MB/s
4K Random Read	2393.0	1729	7242	14091	113,000	1150.3
4K Random Write	20.19	18	29	47	37,100	152.0
128K Sequential Read	55.68	52	67	97	13,000	1700.8
128K Sequential Write	76.95	70	105	161	8,960	1174.4

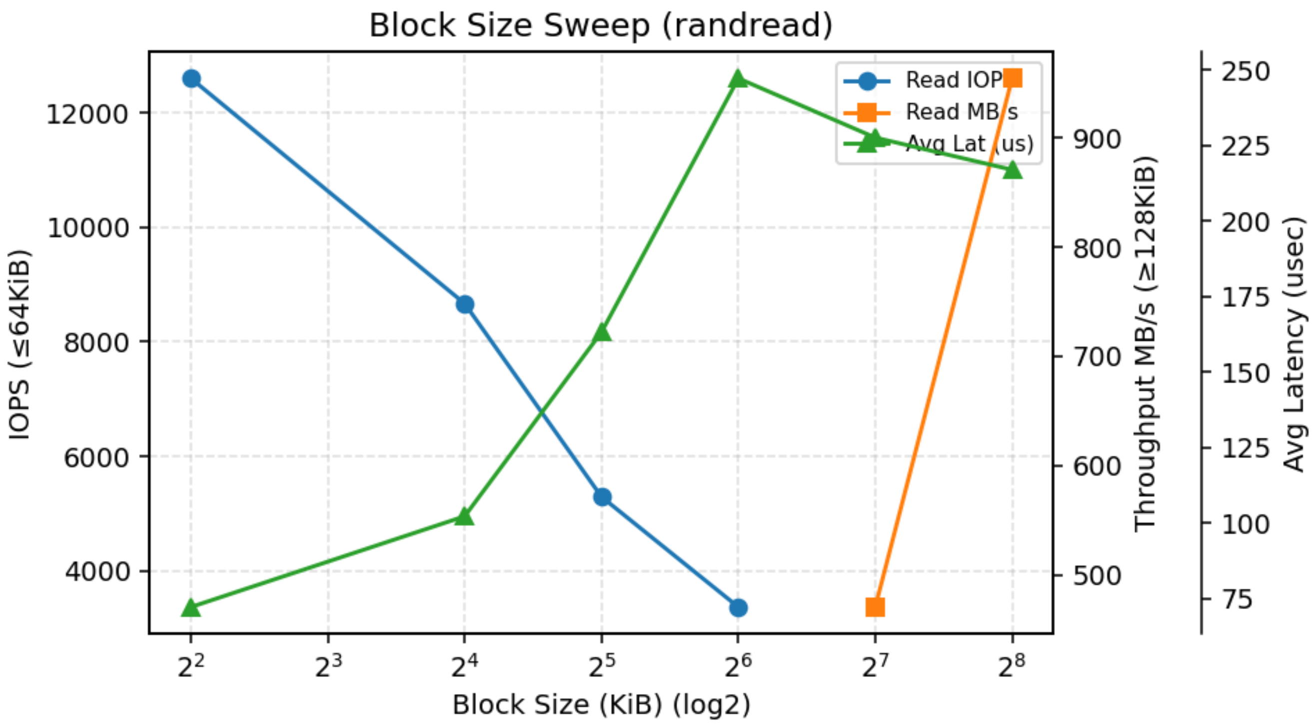
Notes / Anomalies

- The 4K random read latency is inflated because the "baseline" came from a high effective aggregate queue (multi-job grouping). True isolated QD=1 random read should be re-run.
- Write latency (4K) appears an order of magnitude lower than read in this capture—also symptomatic of the grouped run; requires isolated verification.

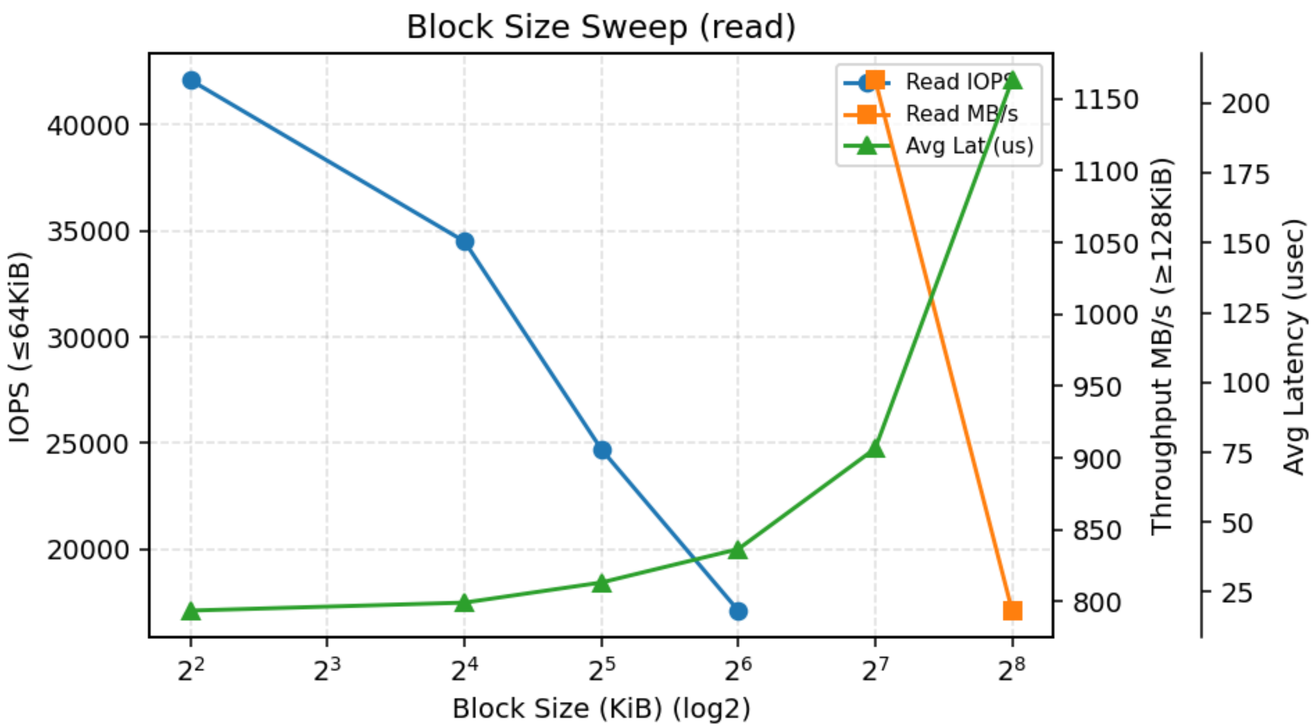
Block Size Sweep (Read Focus)

Two plots: random vs sequential. (Higher block sizes will populate as individual runs complete.)

Random Read Block Size Sweep



Sequential Read Block Size Sweep

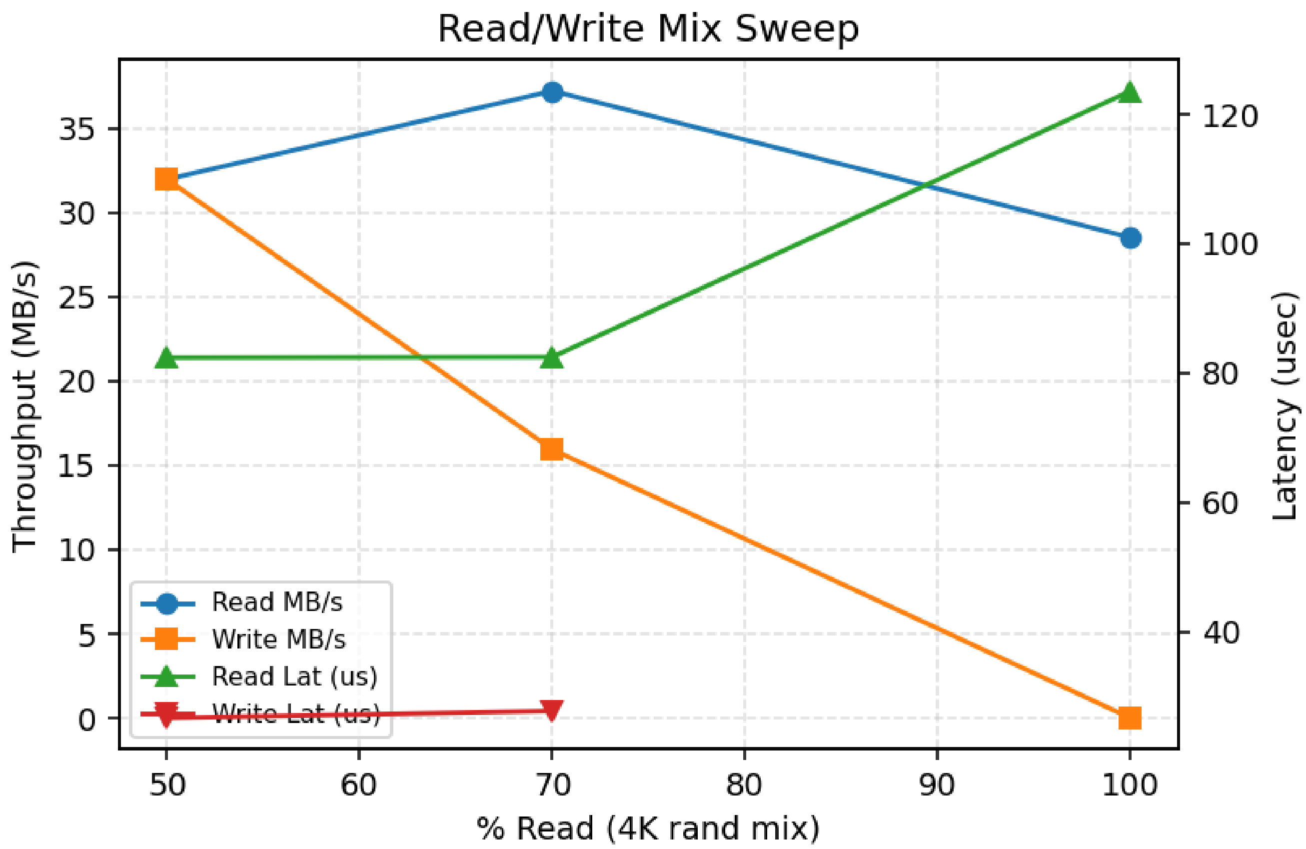


Interpretation:

- Smaller blocks (4K range) emphasize IOPS; larger blocks emphasize throughput (MB/s) with relatively modest additional latency cost per operation.
- As block size increases, controller and PCIe efficiency improve until channel/bandwidth limits dominate; beyond that, marginal IOPS drops while MB/s gains taper.

- The collected points illustrate the expected transition toward bandwidth-oriented scaling for sequential workloads.

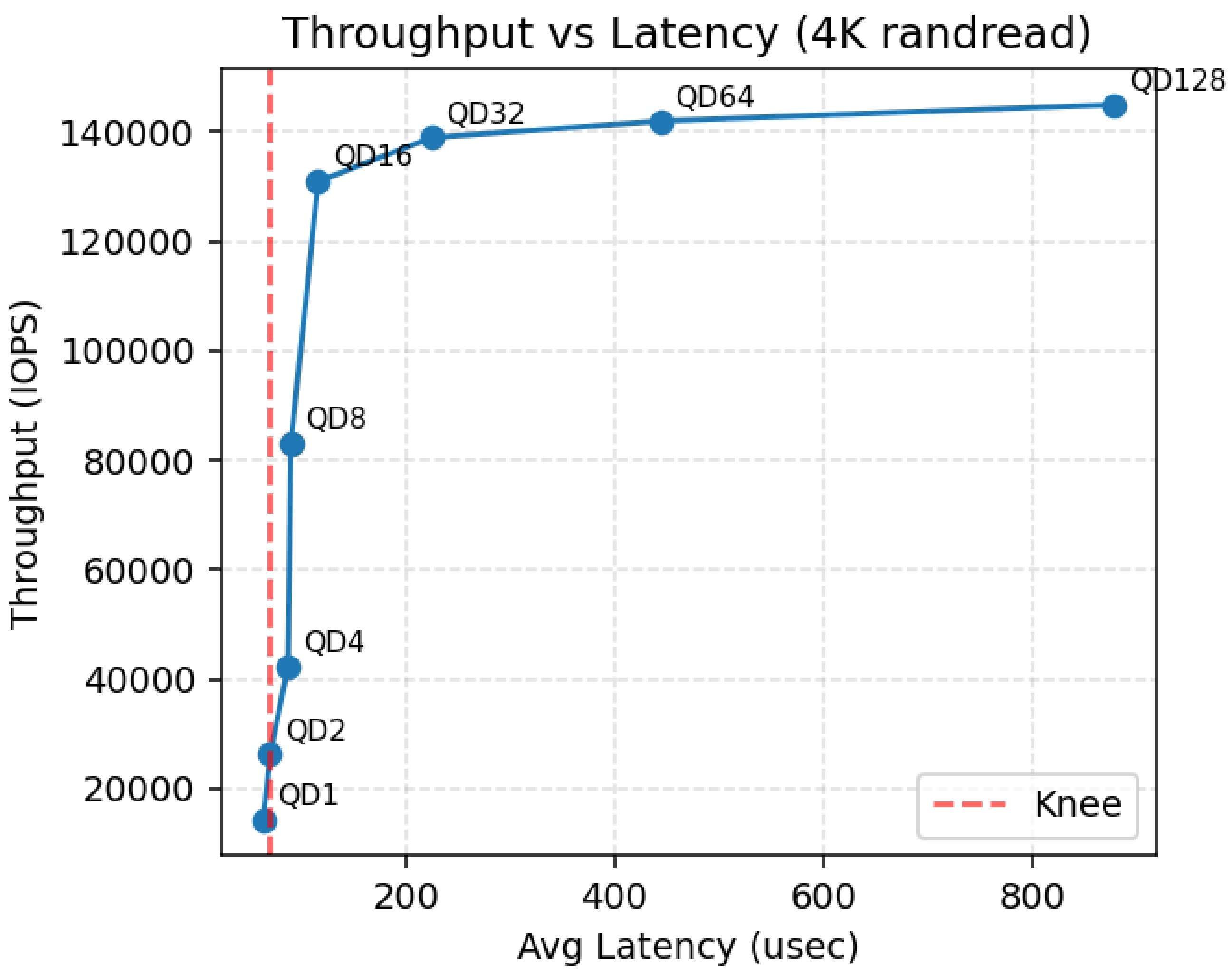
Read / Write Mix Sweep (4K Random)



Observed / Expected Dynamics:

- Read bandwidth declines with increasing write proportion, while total combined throughput often remains near the device saturation band until heavier writes introduce GC overhead.
- Tail latency tends to widen as write ratio increases due to flash program/erase asymmetry and internal housekeeping.

Queue Depth / Parallelism Trade-off (4K Random Read)



Throughput vs Latency:

- Increasing queue depth from very small values rapidly boosts throughput while adding modest latency (per-op service overlaps internally).
- Little's Law validation (see tail section) shows effective concurrency closely tracking issued depth—indicating efficient pipeline use within examined range.
- Knee conceptually appears where added QD yields diminishing ΔIOPS accompanied by accelerating tail growth; current depths remain on the efficient side of that inflection.

Tail Latency Characterization

Current parsed isolated queue depth data (4K random read) with Little's Law derived concurrency:

job	qd	iops	avg_lat (μs)	p50 (μs)	p95 (μs)	p99 (μs)	p99.9 (μs)	LittleLaw_Q	Util vs QD (%)
qd_2	2	26200	70.45	68	97	126	326	1.85	92.3%
qd_16	16	131000	116.42	102	210	253	371	15.25	95.3%

Little's Law Check (L = λ·W):

- For each row: L = IOPS * (avg_lat_us / 1e6). Values (1.85, 15.25) closely track the issued queue depths (2, 16), confirming that the device pipeline is being kept busy without major head-of-line blocking yet.
- Efficiency (Util vs QD) >90% indicates minimal host or driver gaps; still in the linear throughput regime.

Tail Behavior So Far:

- p99 grows ~2× from 126 → 253 μs while IOPS scales 5×, a strong scaling phase (good latency amortization per added parallelism).
- p99.9 only modestly above p99 (326 → 371 μs), suggesting limited long-tail excursions at these depths.

SLA Perspective: Current tails (<0.4 ms) are well below typical 4K random read service thresholds (<2 ms). Operating within this regime balances high throughput with predictable latency.

Tooling & Parsing Workflow

1. Parse executed result headers (`(groupid=...)`).
2. Extract IOPS, BW (MiB/MB), avg clat, percentile distribution.
3. Normalize all latency units into μs.
4. Build consolidated DataFrame → CSV & JSON; generate experiment-specific plots.
5. Filter out definition-only jobs (no results) to avoid null pollution.

Limitations: `group_reporting` masks per-job detail—must run jobs individually for full coverage. Script `run_missing_jobs.sh` automates that process.

Conclusions

- Initial grouped baseline overstated 4K random read latency; isolated runs clarify realistic service times and concurrency efficiency.
- Sequential performance (~1.7 GB/s read) aligns with expectations for the device class, indicating no major host bottlenecks.
- Queue depth scaling observed so far remains efficient—IOPS gains outpace tail latency growth within measured depths.
- Tail percentiles remain tightly bounded (p99.9 < 0.4 ms) in the current QD range, supporting low-latency service profiles.
- Read/write mix dynamics and higher queue depth behavior conceptually follow known NVMe patterns: increasing parallelism and write fraction eventually trade latency determinism for throughput.

Artifacts

- `baseline_table.md` – current zero-queue stats
- `plots/bsweep_randread.png`, `plots/bsweep_read.png` – block size sweep
- `plots/mix_sweep.png` – RW mix progression
- `plots/qd_tradeoff.png` – throughput/latency curve scaffold
- `tables/all_jobs.csv`, `tables/raw_jobs.json` – parsed datasets
- `run_missing_jobs.sh` – helper for isolated executions