NUTANIX

Storage Performance Review *for Hypervisors*

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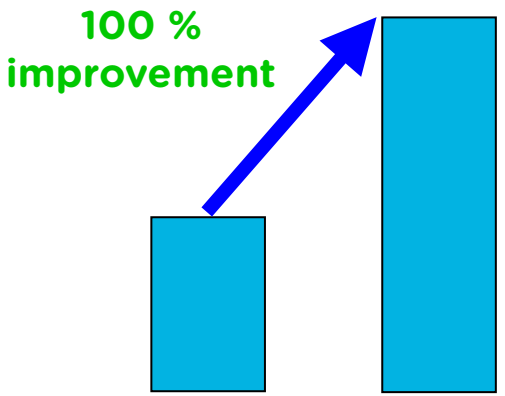
Performance Overhead

Performance Overhead

-25%

5 X
FASTER



Storage Performance Overhead

Depends on:

- Direction of I/O (read / write)
- Size of I/O (..., 4K, ..., 1M, ...)
- Sequence of I/O (sequential / random)
- Queue Depth (# of I/Os outstanding)
  - Batched I/Os
  - Number of threads
  - QD per thread
- Handling Fairness (multiple sources)
- Submission interface (libaio, io_uring, spdk)
- I/O Duration (sustained performance)
- Temperature [1]
- Noise / Vibration [2]
- Interrupt distribution
  - Depending on CPU utilisation
- Cache contention (O_DIRECT)
- NUMAness
- Lock contention
- Backend (Null / HDD / SSD / Net)

[1] "... why some (might) like it hot" dl.acm.org/citation.cfm?id=2254778

[2] "Shouting in the Datacenter" youtu.be/tDacjrSCeq4

Agenda

1 Measuring Storage Performance

2 Analysing Virtualisation Overhead
(and a brief Hypervisor Analysis)

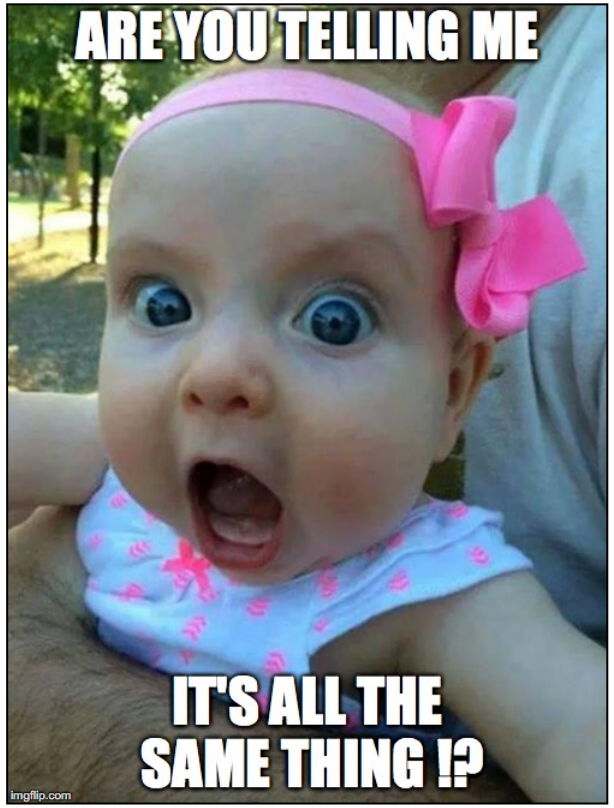
3 Conclusions, Thoughts, and Extras

Measuring Storage Performance

Measuring Storage Performance

What are we really measuring?

- Bandwidth or Throughput (MB/s)
- IOPS (reqs/s)
- Latency (us)



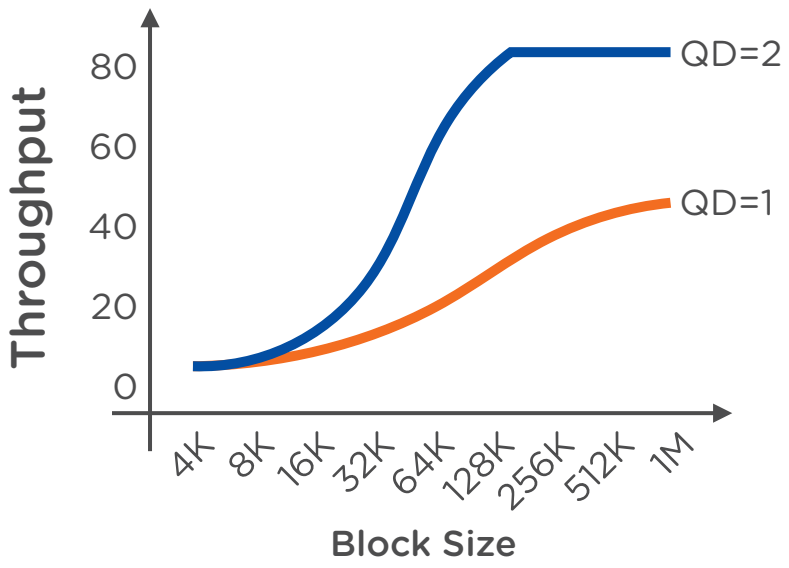
(MB/s) $\frac{\text{data}}{\text{time}}$

(reqs/s) $\frac{\text{data}}{\text{time}}$

(us/req) $\frac{\text{time}}{\text{data}}$

Measuring Storage Performance

Measuring Throughput

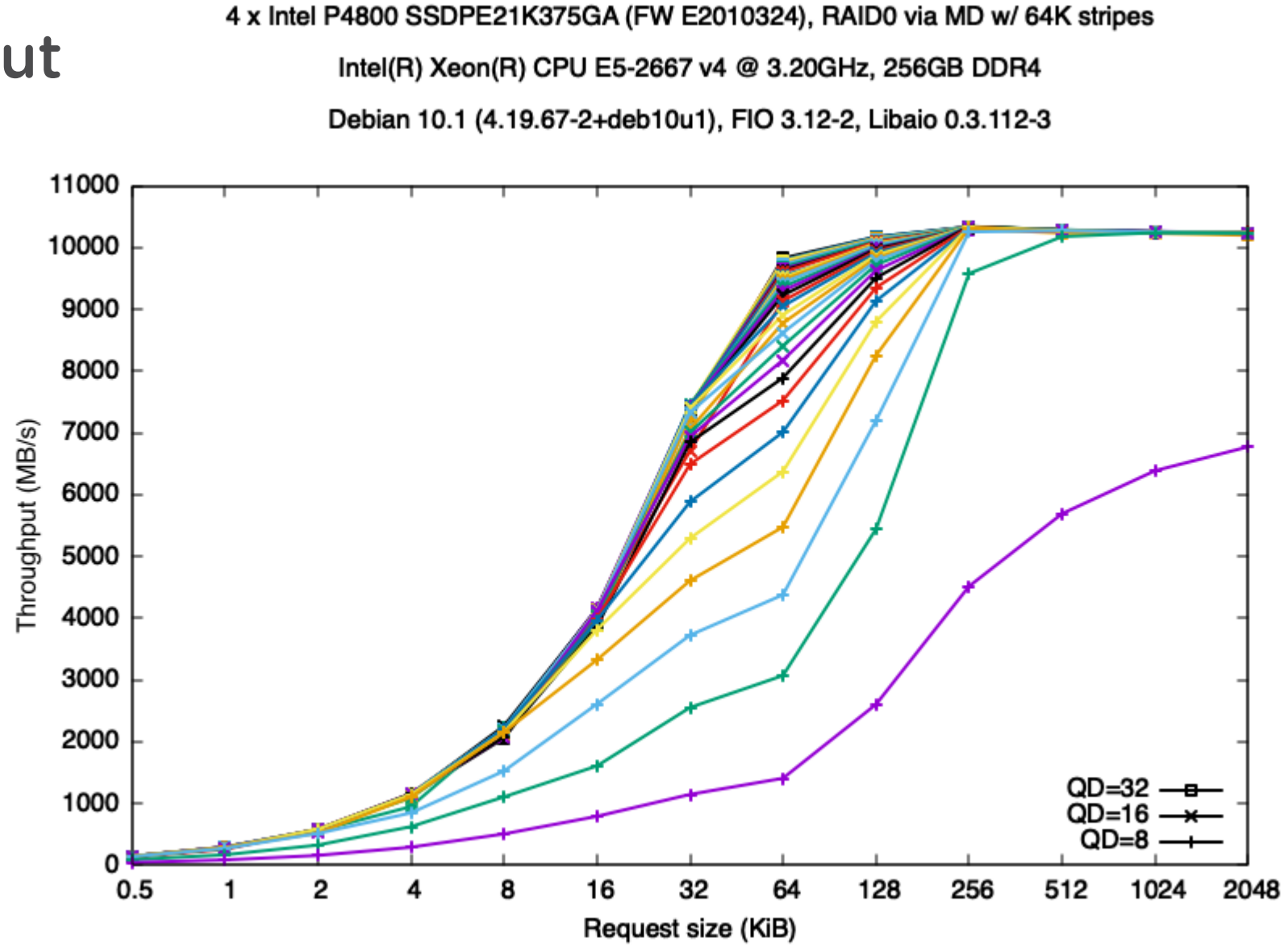


- Usually associated with sequential I/O (and large requests)
  - When access pattern is known, data can be transferred in bulk
  - Transferring contiguous large datasets favours HDD
- Modern SSDs are not saturated with QD 1
  - Worth measuring higher QDs, in steps of 1
  - Doesn't *normally* saturate CPUs, but it can
  - Pinning should be observed to avoid NUMAness
- Plotting the graph
  - Y-Axis linear scale (MB/s)
  - X-Axis log scale (KiB)
  - Series varying QD (1 or more CPUs)

Measuring Storage Performance

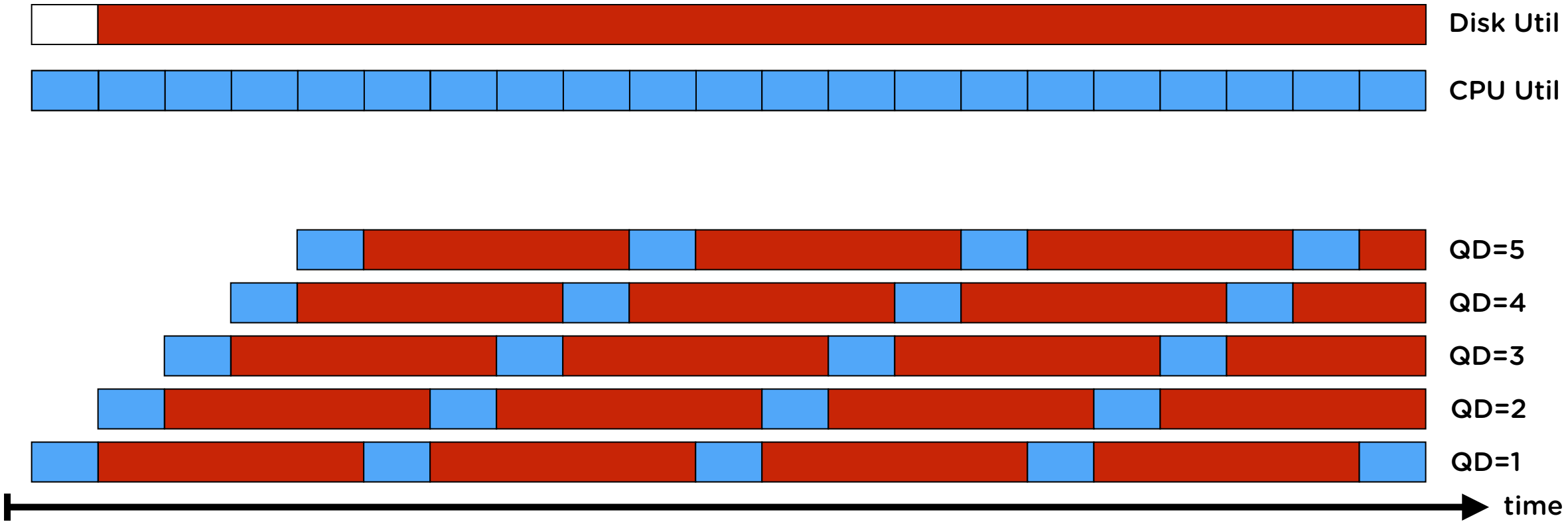
Measuring Throughput

- Direction: Read
- Sequence: Random
- Interface: libaio
- Req size: 512 B ... 2 MiB
- Num threads: 1
  - QD/thread: 1 ... 32
- Thread pinned to CPU 8 (in drive's NUMA node)



Measuring Storage Performance

Saturating CPUs and NVMe (when CPU usage is inefficient)



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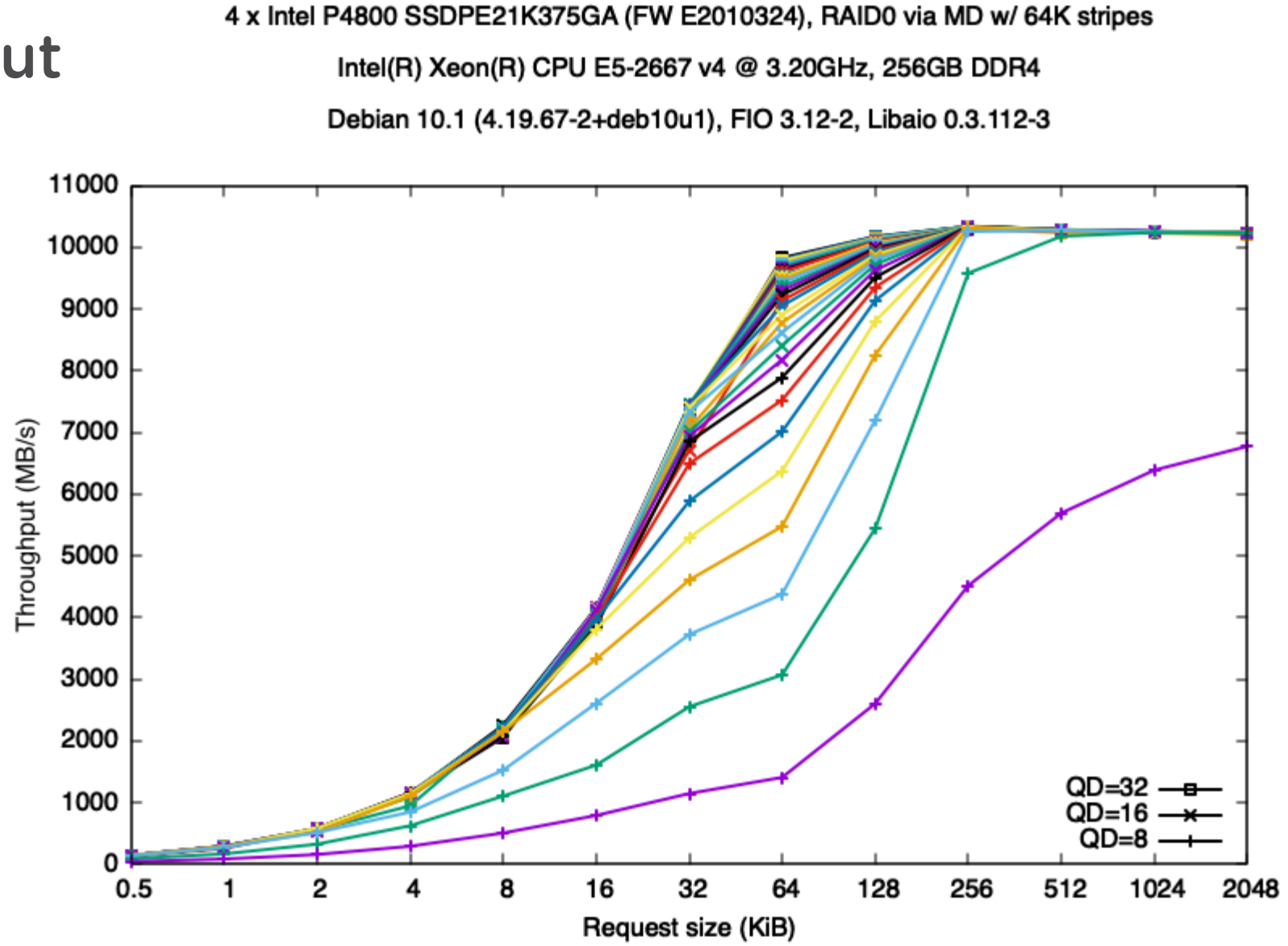

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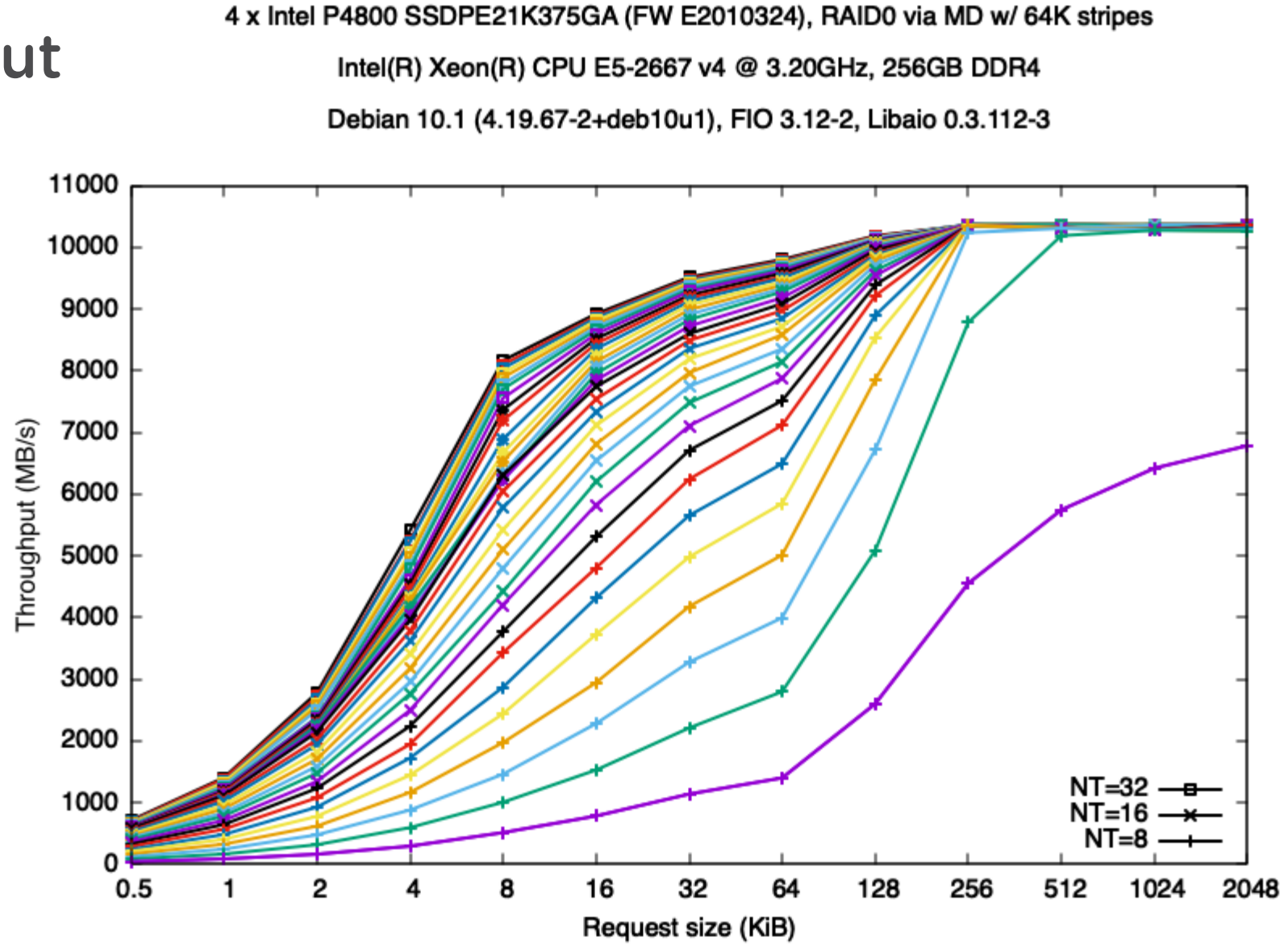
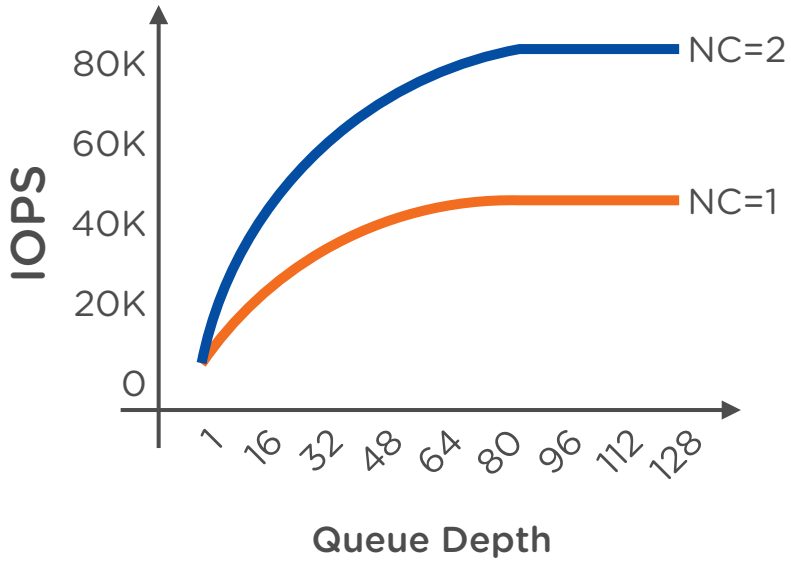


Measuring Storage Performance

Measuring IOPS

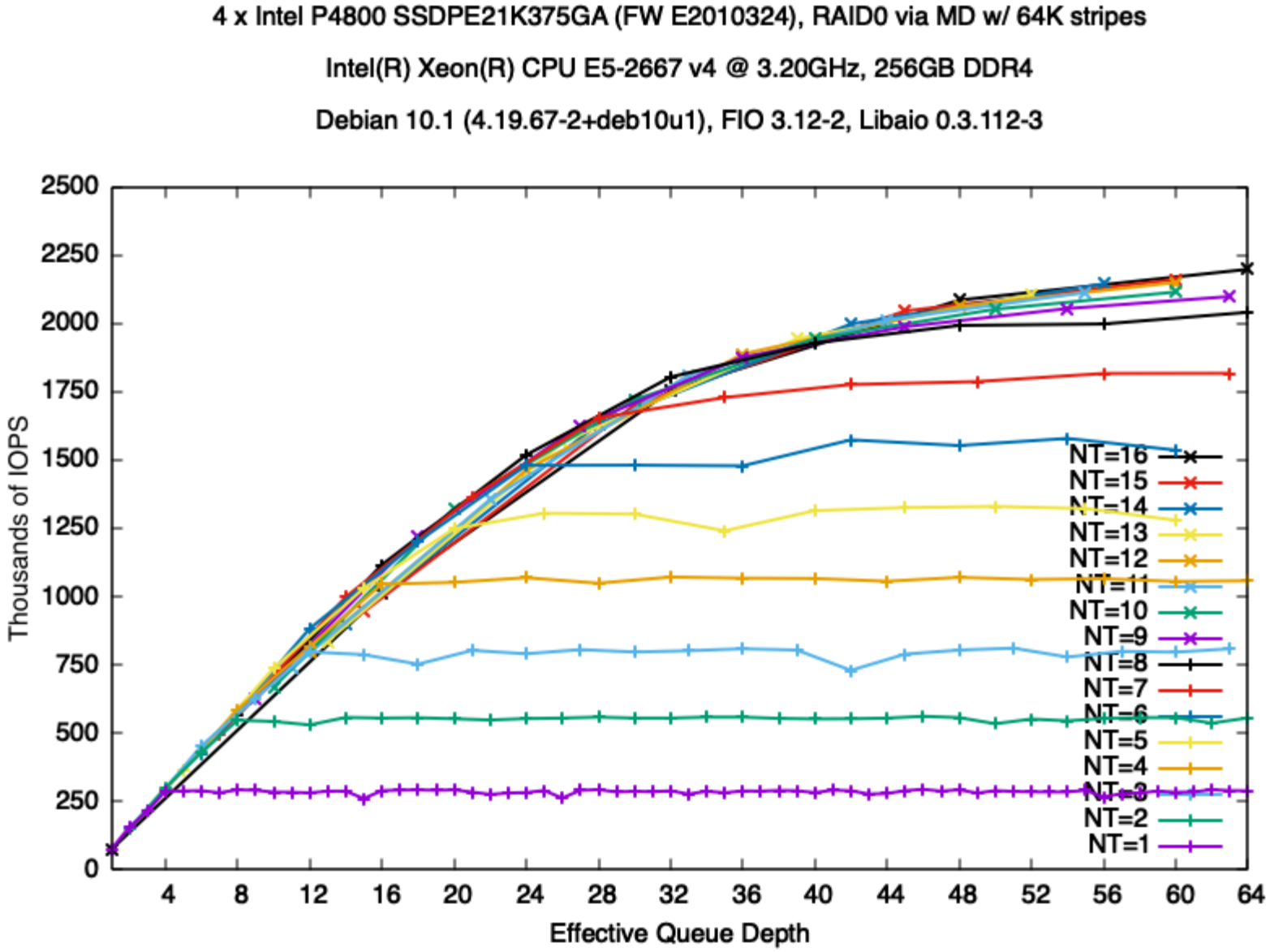


- Usually associated with random I/O (and small requests)
  - When access pattern is unknown, data cannot be transferred in bulk
  - Transferring small datasets randomly disfavours HDD
- Modern SSDs are not saturated with 1 CPU (using kernel + libaio)
  - Worth measuring with more CPUs, in steps of 1
  - Leaner drivers (SPDK, io_uring) are much more efficient
  - Pinning should be observed to avoid NUMAness
- Plotting the graph
  - Y-Axis linear scale (reqs/s)
  - X-Axis linear scale (QD)
  - Series varying number of CPUs (NC)
  - Fixed request size (4 or 8 KiB)

Measuring Storage Performance

Measuring IOPS

- Direction: Read
- Sequence: Random
- Interface: libaio
- Req size: 4 KiB
- Num threads: 1 ... 16
  - QD/thread: 1 ... 64
- Thread(s) pinned to CPUs 8-15 (in drive's NUMA node)



Analysing Virtualisation Overhead

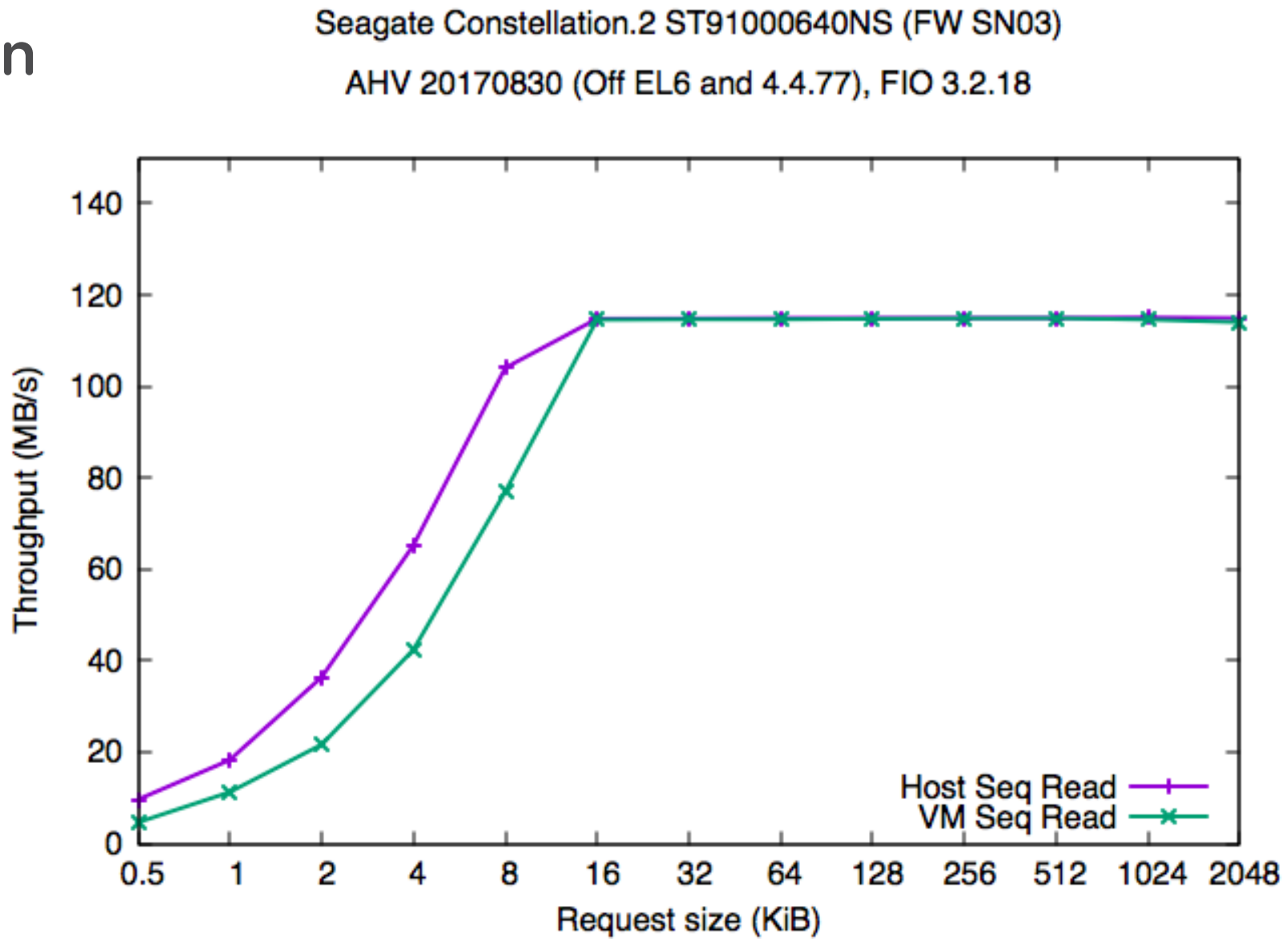
Analysing Virtualisation Overhead

Overhead Illustration

- **Measuring Throughput**
  - Mechanical drive
  - Sequential reads
  - QD = 1
  - Req size: 512 B ... 2 MiB

And from a VM ?

- Debian 9.4 VM (FIO 3.2.18)
- Host with Qemu 2.6
- Disk over virtio-scsi

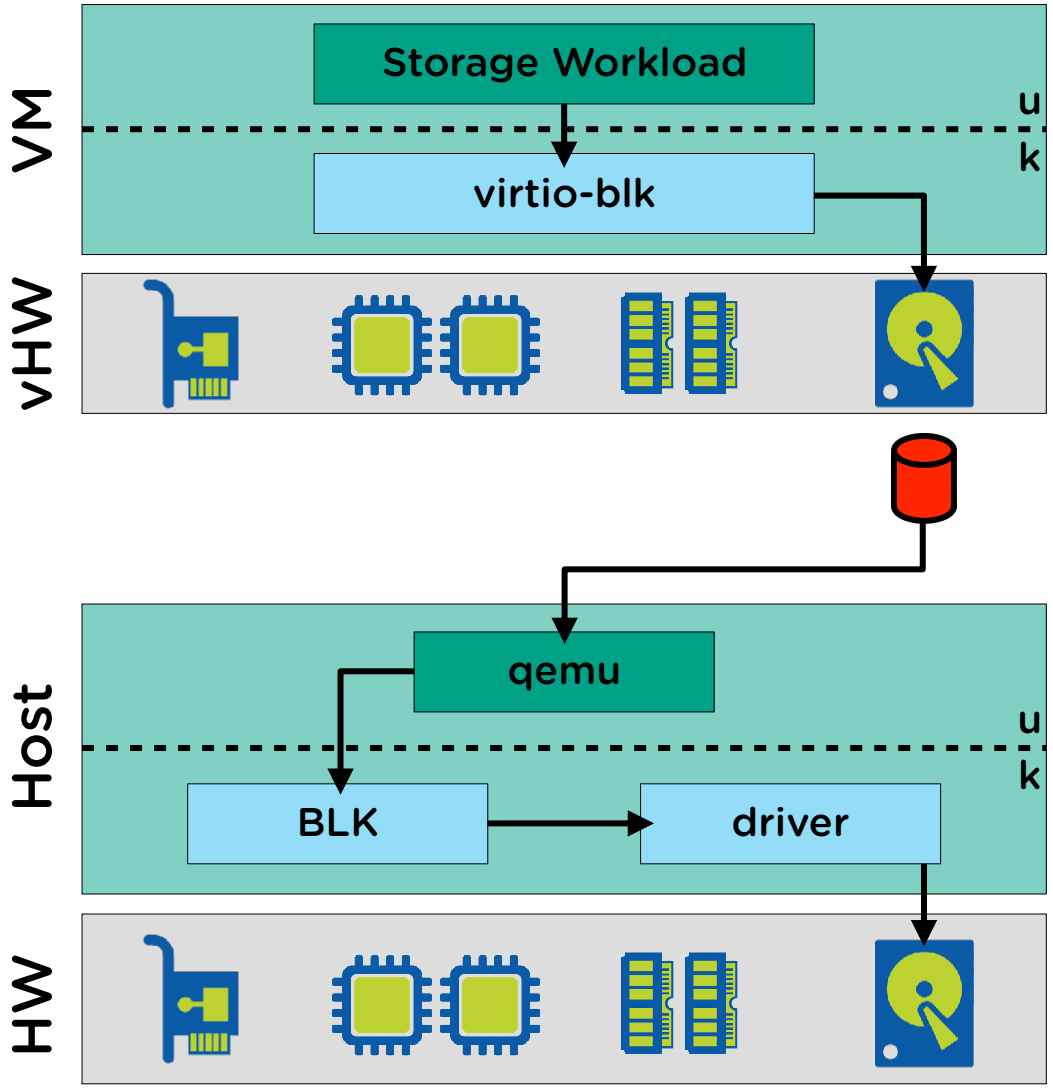


Analysing KVM + Qemu

1 VM on Qemu 3.1.0

w/ 1 vDisk on virtio-blk

Hypervisor Analysis: KVM + Qemu



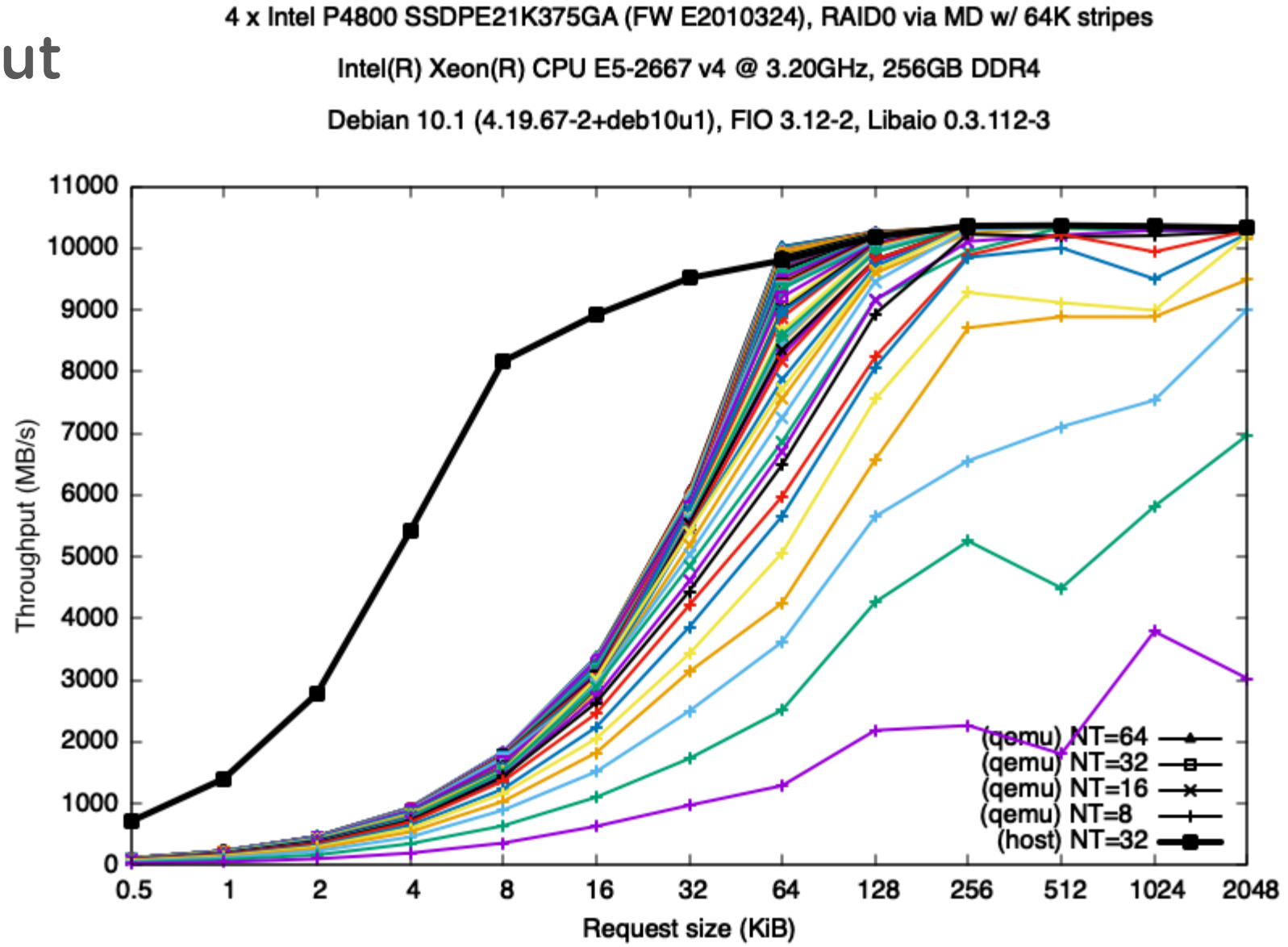
Typical virtio-blk deployment

- One controller per disk presented to VM
- Disks are block devices
- One controller cannot use multiple I/O threads
  - The I/O thread bottlenecks on CPU
  - In order to scale, VM requires more controllers (and more virtual disks and more I/O threads)

Hypervisor Analysis: KVM + Qemu

Measuring Throughput

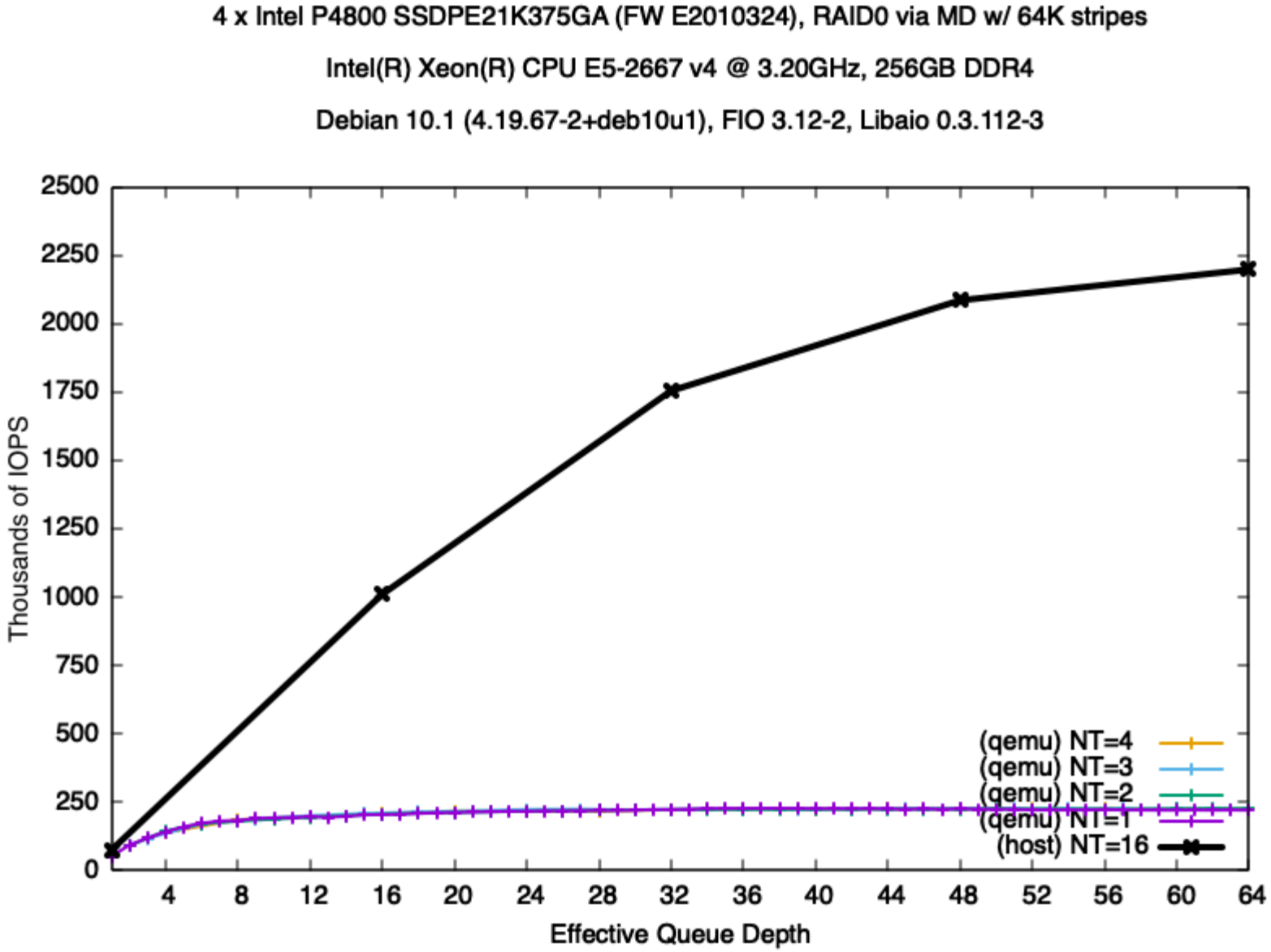
- Direction: Read
- Sequence: Random
- Interface: libaio
- Req size: 512 B ... 2 MiB
- Num threads: 32
  - QD/thread: 1
- Thread(s) pinned to CPUs 8-15 (in drive's NUMA node)
- VM (Qemu 3.1.0, virtio-blk)
  - Num threads: 1 ... 64
  - QD/thread: 1
  - VM pinned to CPUs 8-15



Hypervisor Analysis: KVM + Qemu

Measuring IOPS

- Direction: Read
- Sequence: Random
- Interface: libaio
- Req size: 4 KiB
- Num threads: 16
  - QD/thread: 1 ... 64
- Threads pinned to CPUs 8-15 (in drive's NUMA node)
- VM (Qemu 3.1.0, virtio-blk)
  - Num threads: 1 ... 4
  - QD/thread: 1 ... 64
  - VM pinned to CPUs 8-15

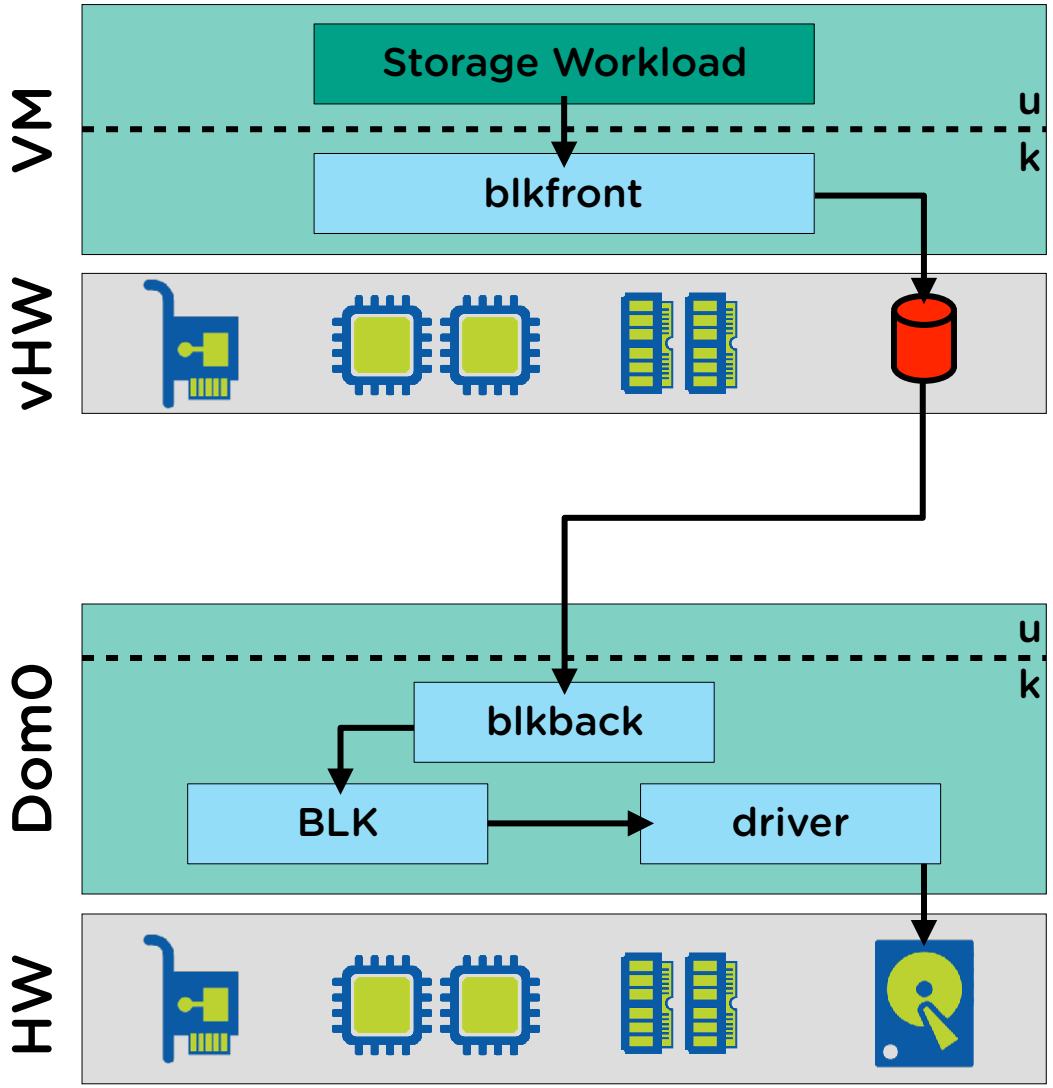


Analysing Xen + Blkback

1 VM on Qemu 3.1.0

1 vDisk on Blkfront/Blkback

Hypervisor Analysis: Xen + Blkback



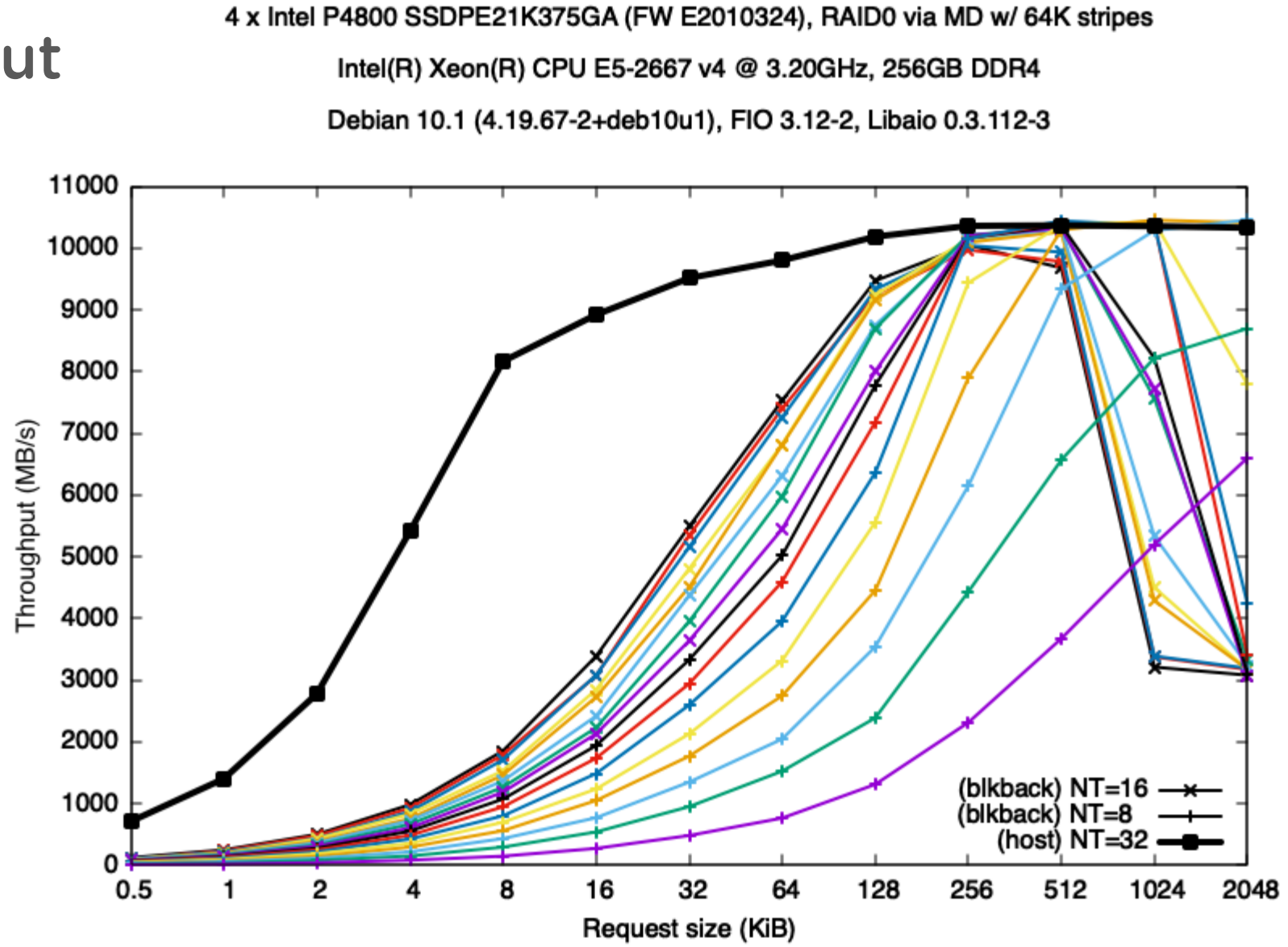
Typical blkback deployment

- Disks are block devices on XenBus
- Blkback has a queue for each guest vCPU
  - This allows performance to scale with VM size
  - But it eats a lot of CPU on Domain 0
- The Xen block ring interface has design deficiencies
  - Limitations on the number of outstanding requests
    - Multi-page rings can help
  - Limitations on the request size
    - Indirect descriptors can help
- Xen requires memory to granted by frontend and mapped by backend. This contributes to overhead.
  - Persistent grants can help

Hypervisor Analysis: Xen + Blkback

Measuring Throughput

- Direction: Read
- Sequence: Random
- Interface: libaio
- Req size: 512 B ... 2 MiB
- Num threads: 1 ... 32
  - QD/thread: 1
- Thread(s) pinned to CPUs 8-15 (in drive's NUMA node)
- VM (Qemu 3.1.0, blkback)
  - Num threads: 1 ... 16
  - QD/thread: 1
  - VM pinned to CPUs 8-15



Hypervisor Analysis: Xen + Blkback

Measuring IOPS

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- Sequence: Random
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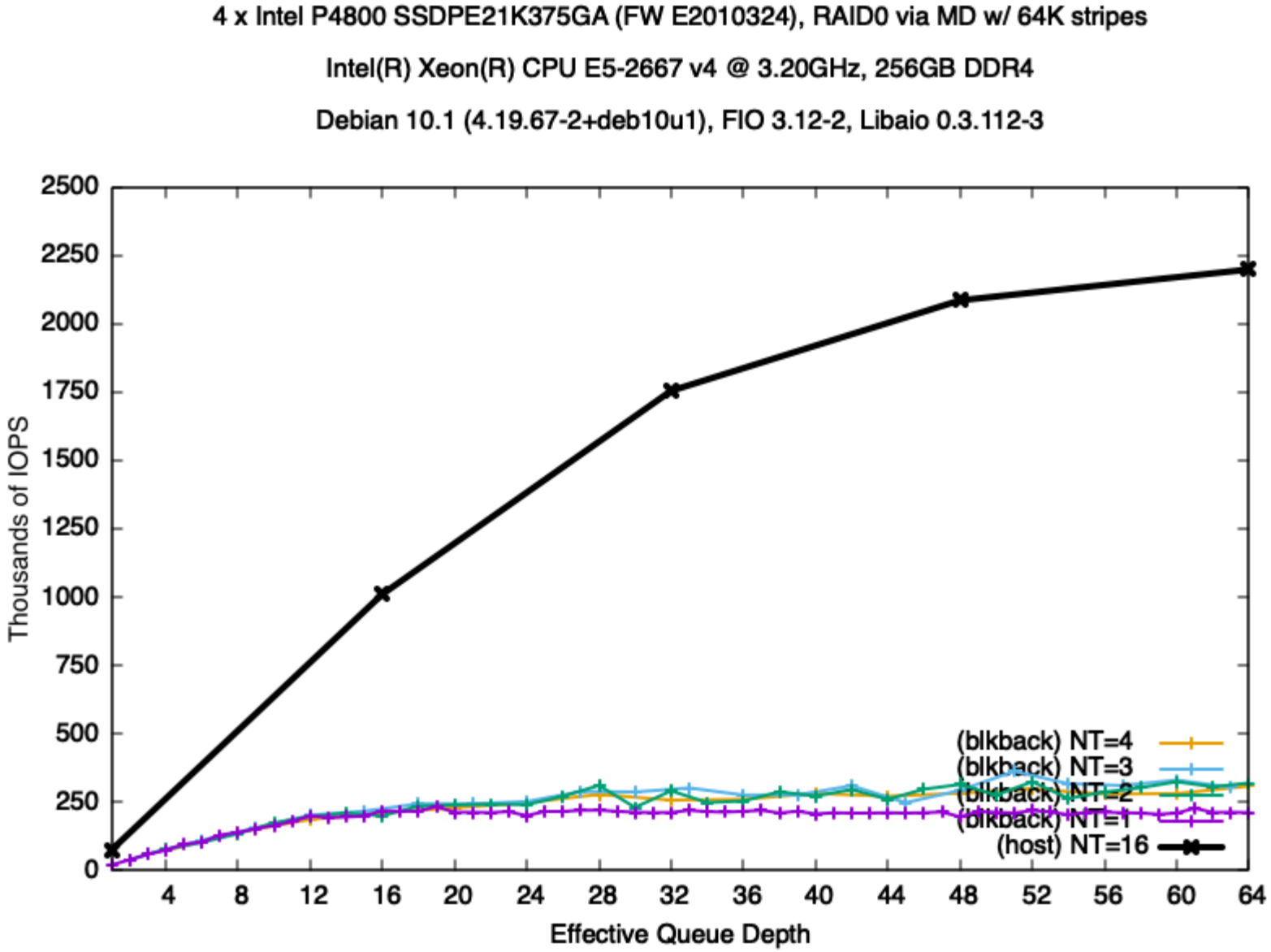


Conclusions, Thoughts, and Extras

Conclusions, Thoughts, and Extras

- Low-latency, high-throughput storage is hard to virtualise
  - Traditional kernel datapaths consume too much CPU
  - Datapath from application to storage must be more **efficient**

- KVM
  - Emulators have direct access to VM memory by default
  - VirtIO + MQ can work great if emulator is parallel and efficient
  - NVMe is an attractive solution due to industry support on standard

- Xen
  - Is too focused on security, not allowing VM memory access by default
  - Xen's ring format should be revisited to align with modern device models
  - Blkback is efficient (entirely in-kernel datapath), but apparently has contention problems

Conclusions, **Thoughts**, and Extras

- How can hypervisors be more efficient?
  - **First thing**: avoid legacy kernel datapaths (ie. libaio, read()/write() syscalls)
    - There are more attractive solutions with io_uring or SPDK
  - **Second thing**: pursue hardware offload or software host polling
    - Hardware offload means that VFs can be passed-through to VMs
    - Host polling means that:
      - One process* handles I/O from all VMs on host
      - This process polls VMs' submission queues in a tight loop
      - VMs don't have to kick the hypervisor (saves on VM EXITs)
      - Hypervisor doesn't require IRQs from devices (saves on ctx switches)
    - Additionally, VMs that care about performance can also poll
      - VMs don't require IRQs from hypervisor (saves on ctx switches)

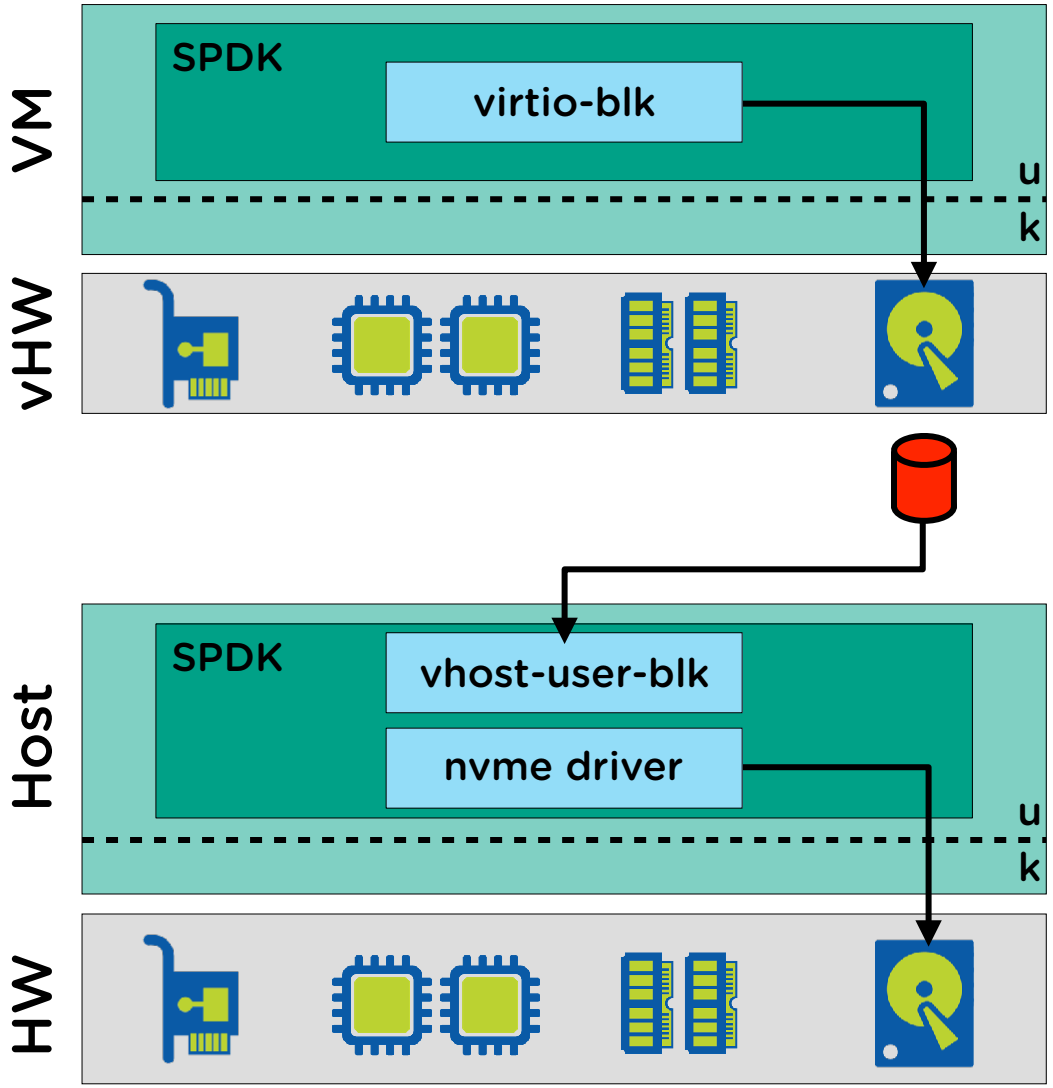
* Multi-tenant hosts (or similar setups) could have a poller per tenant

EXTRAS: Analysing KVM + Qemu

1 VM on Qemu 3.1.0

1 vDisk on SPDK (vhost-user-blk)

Hypervisor Analysis: KVM + Qemu + SPDK



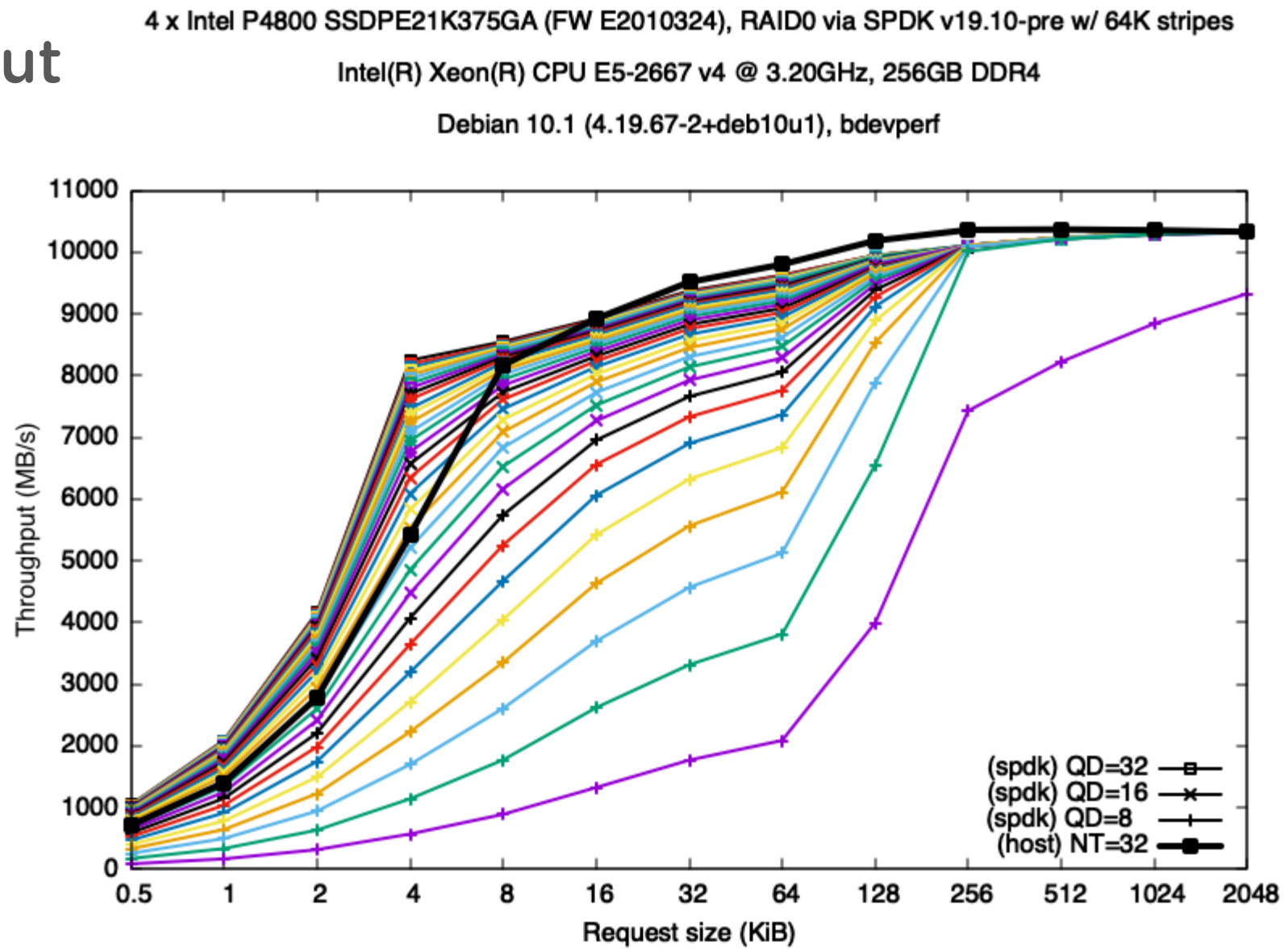
SPDK virtio-blk deployment

- Qemu responsible for configuring virtio-blk device
- Datapath (ie. VQs) offloaded to SDPK via vhost
- One SPDK application per host
  - Many VMs can be driven by one/few thread which:
  - Polls VMs' VQs (no VM EXITs)
  - Directly accesses NVMe devices
  - Polls NVMes CQs (no IRQs)
  - IRQs the guests for completions
    (if guest is polling, no IRQs are required)
- Drawback: NVMes dedicated to this application
  - Totally OK for hypervisors (NVMes are for VM data)

Baseline using SPDK

Measuring Throughput

- Direction: Read
- Sequence: Random
- Interface: SPDK
- Req size: 512 B ... 2 MiB
- Num threads: 1
  - QD/thread: 1 ... 32
- Thread pinned to CPUs 8 (in drive's NUMA node)



Hypervisor Analysis: KVM + Qemu + SPDK

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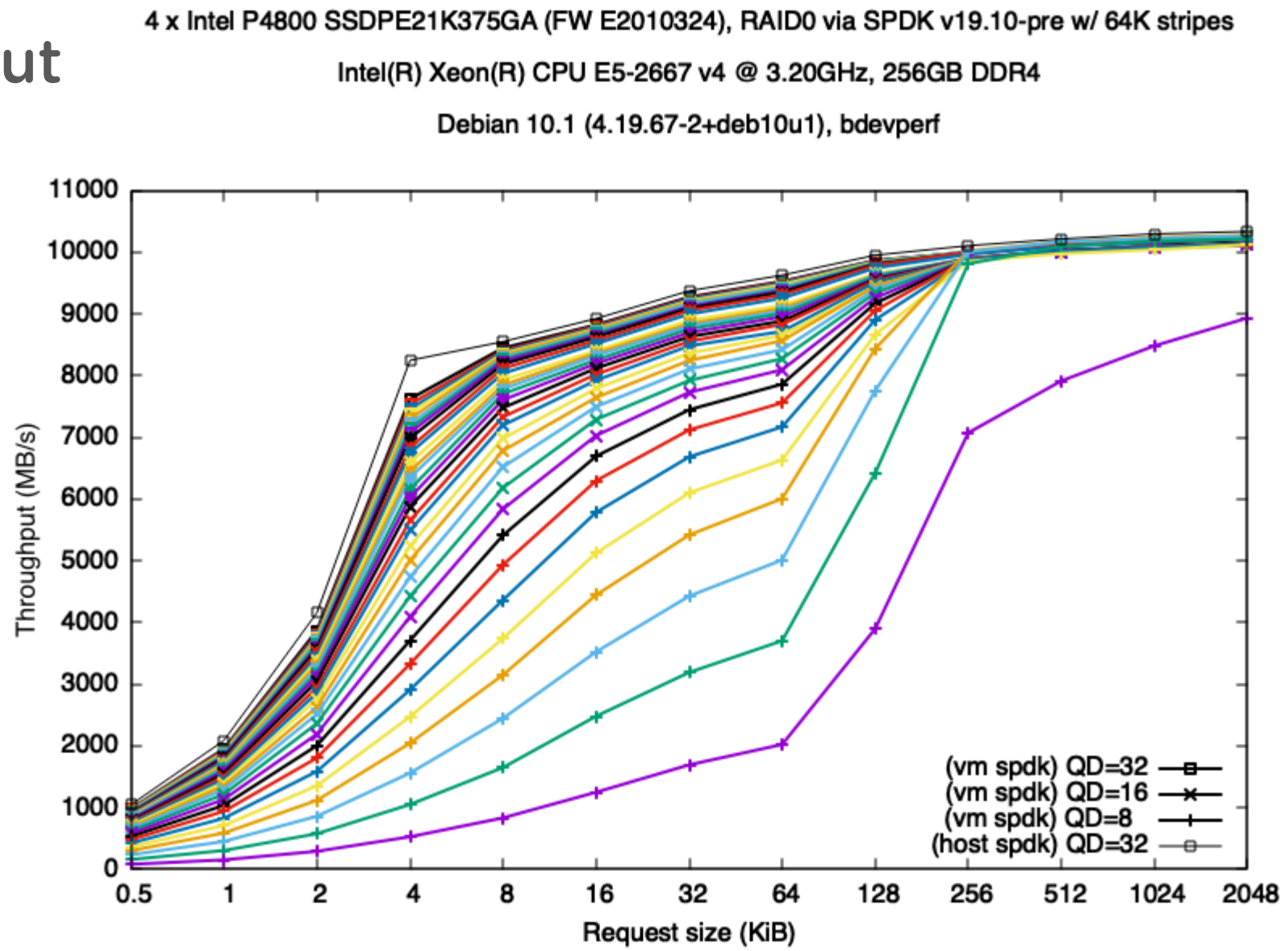

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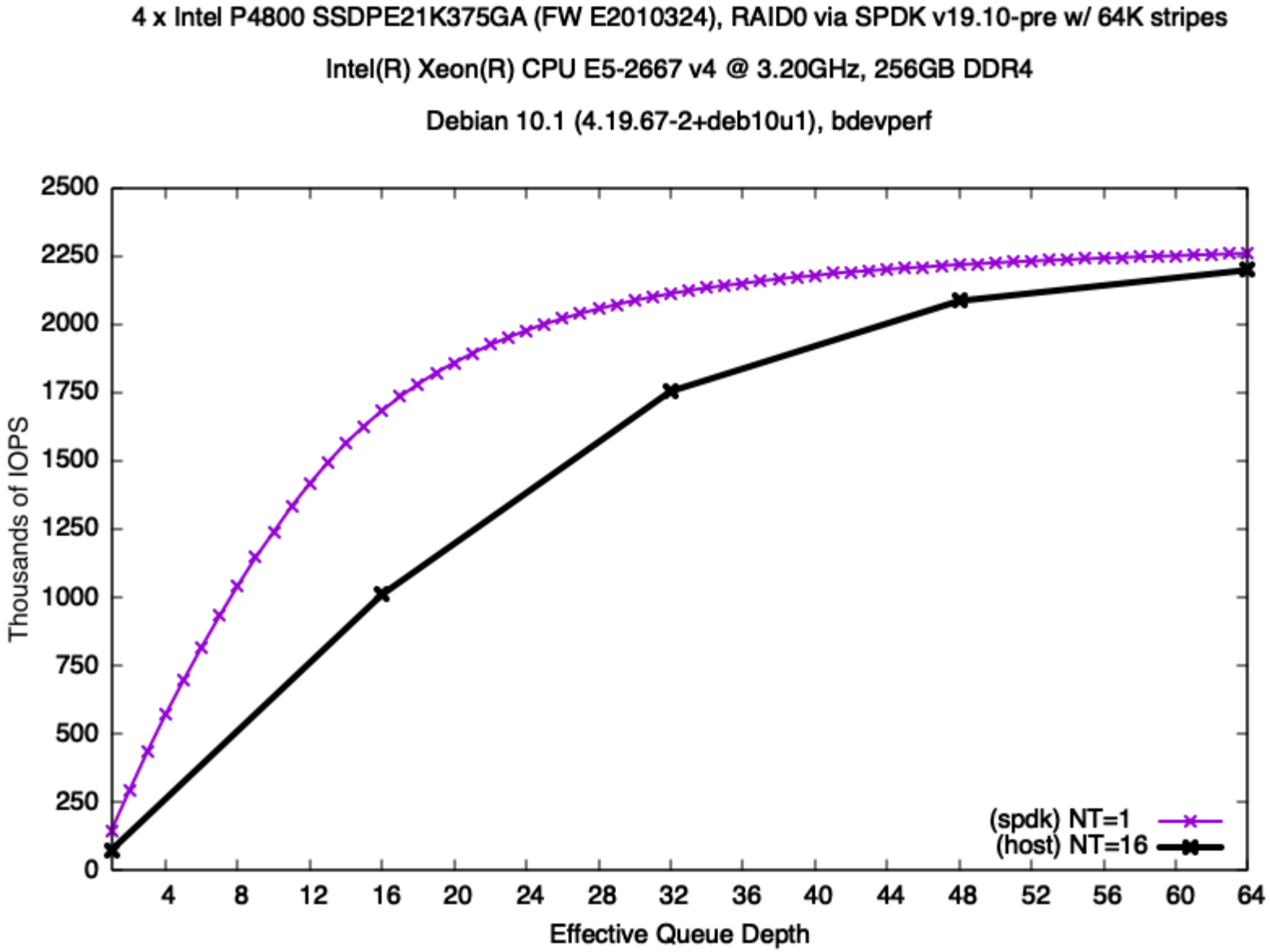

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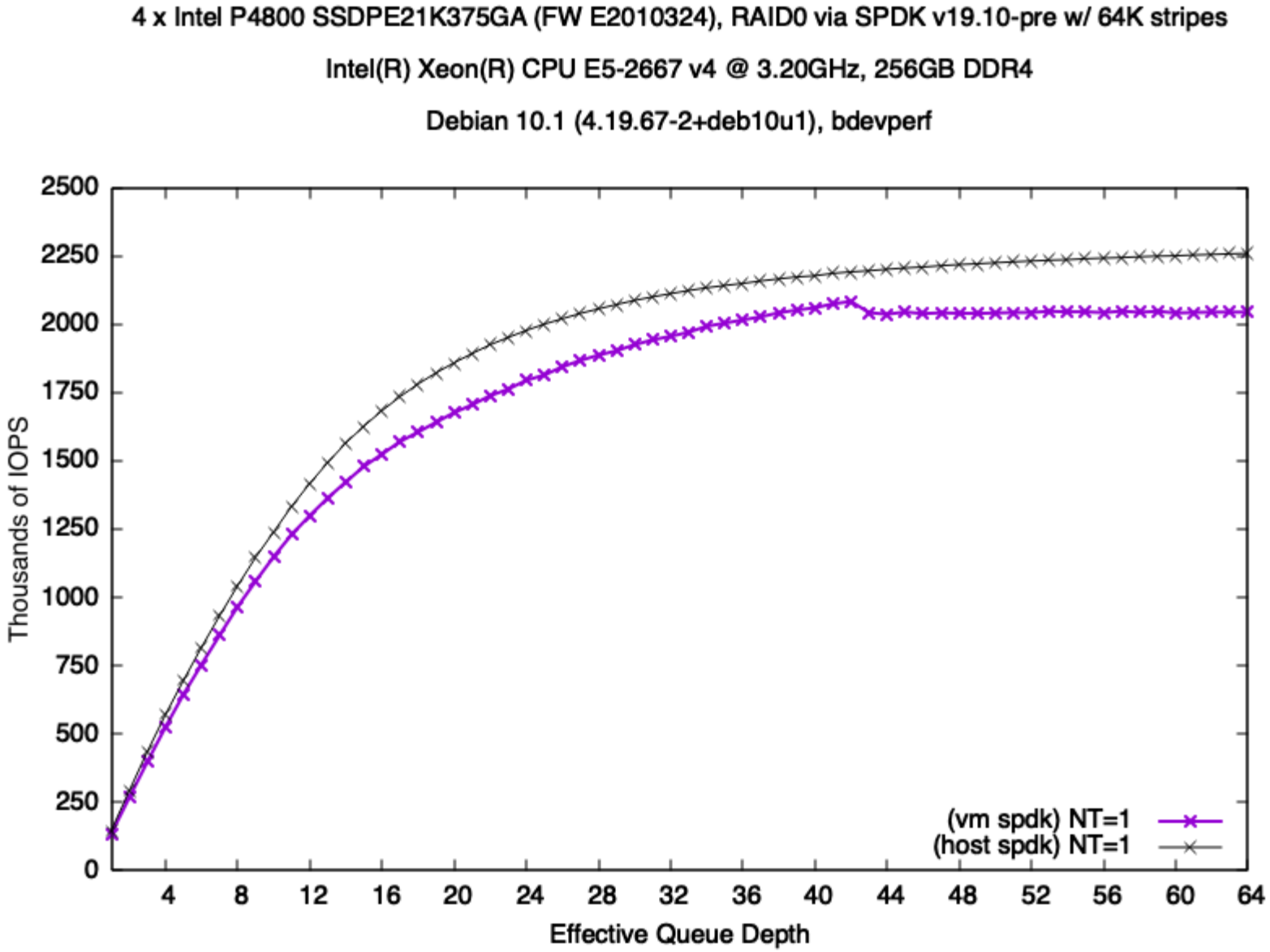

Thank you