Userspace NVMe Driver in QEMU

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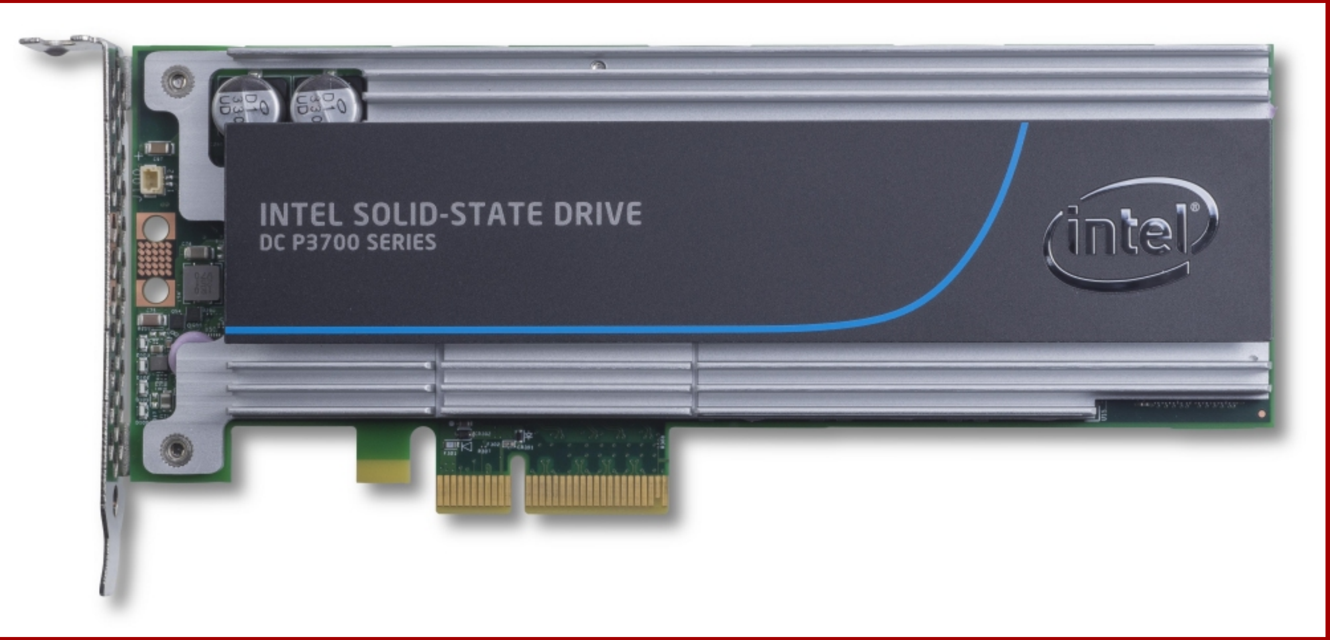
About NVMe

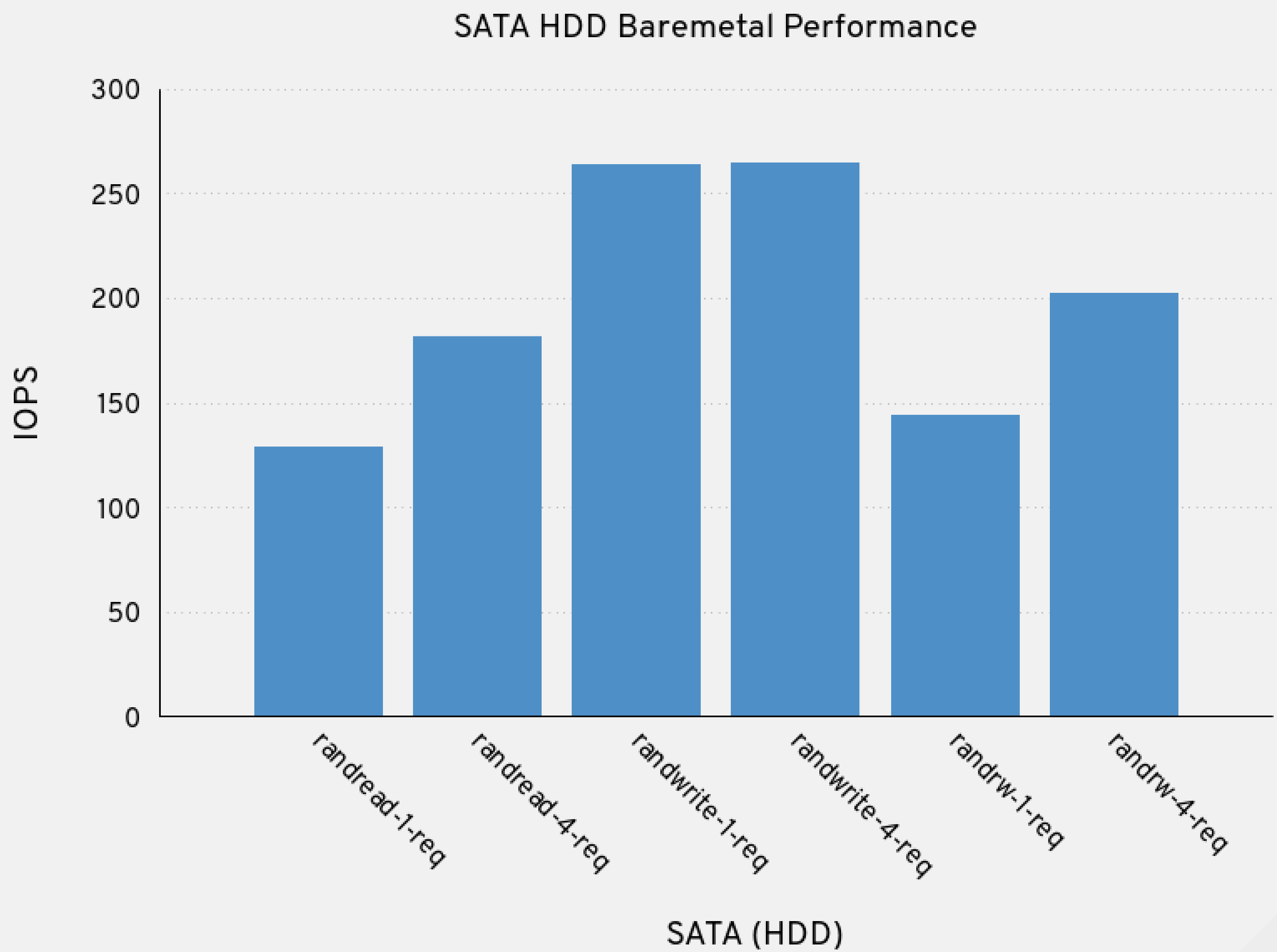
- Non-Volatile Memory Express
- A scalable host interface specification like SCSI and virtio
  - Up to 64k I/O queues, 64k commands per queue
  - Efficient command issuing and completion handling
- Extensible command sets
- Attached over PCIe, M.2 and fabrics (FC, RDMA)

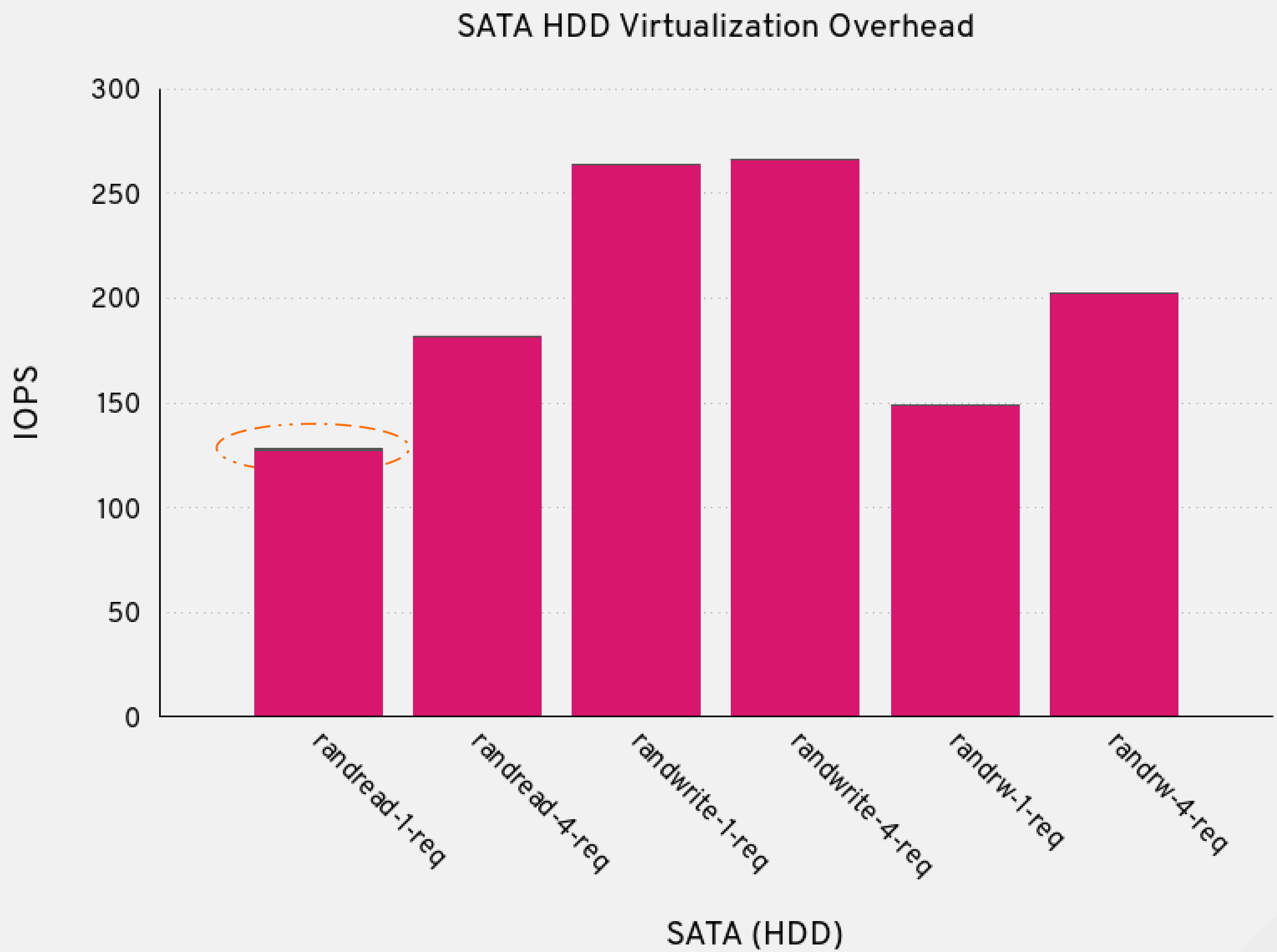


redhat.

Why?

Overhead


SATA HDD Baremetal Performance
300
250
200
150
100
50
0
IOPS
randread-1-req
randread-4-req
randwrite-1-req
randwrite-4-req
randrw-1-req
randrw-4-req
SATA (HDD)


SATA HDD Virtualization Overhead
300
250
200
150
100
50
0
IOPS
randread-1-req
randread-4-req
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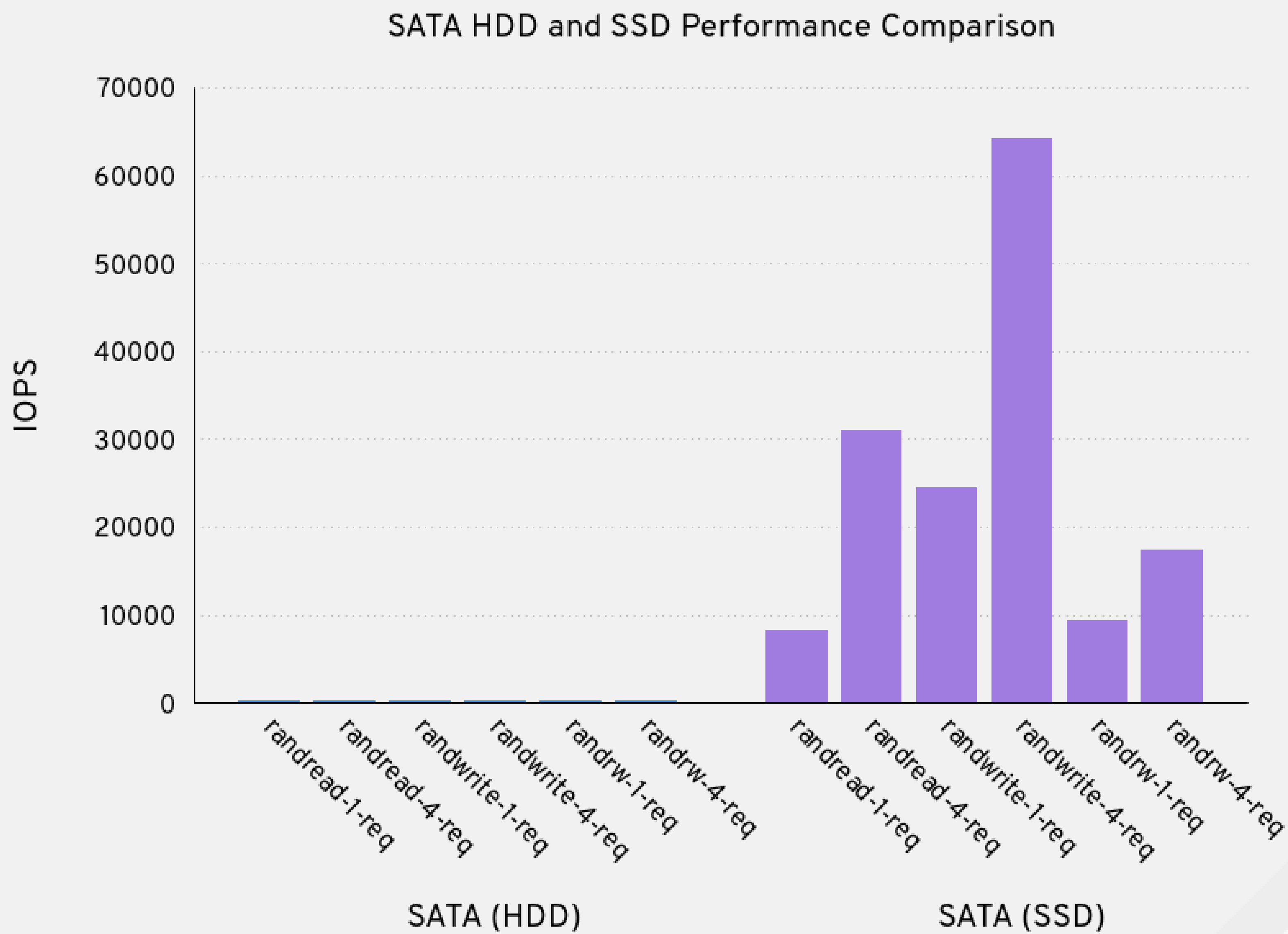
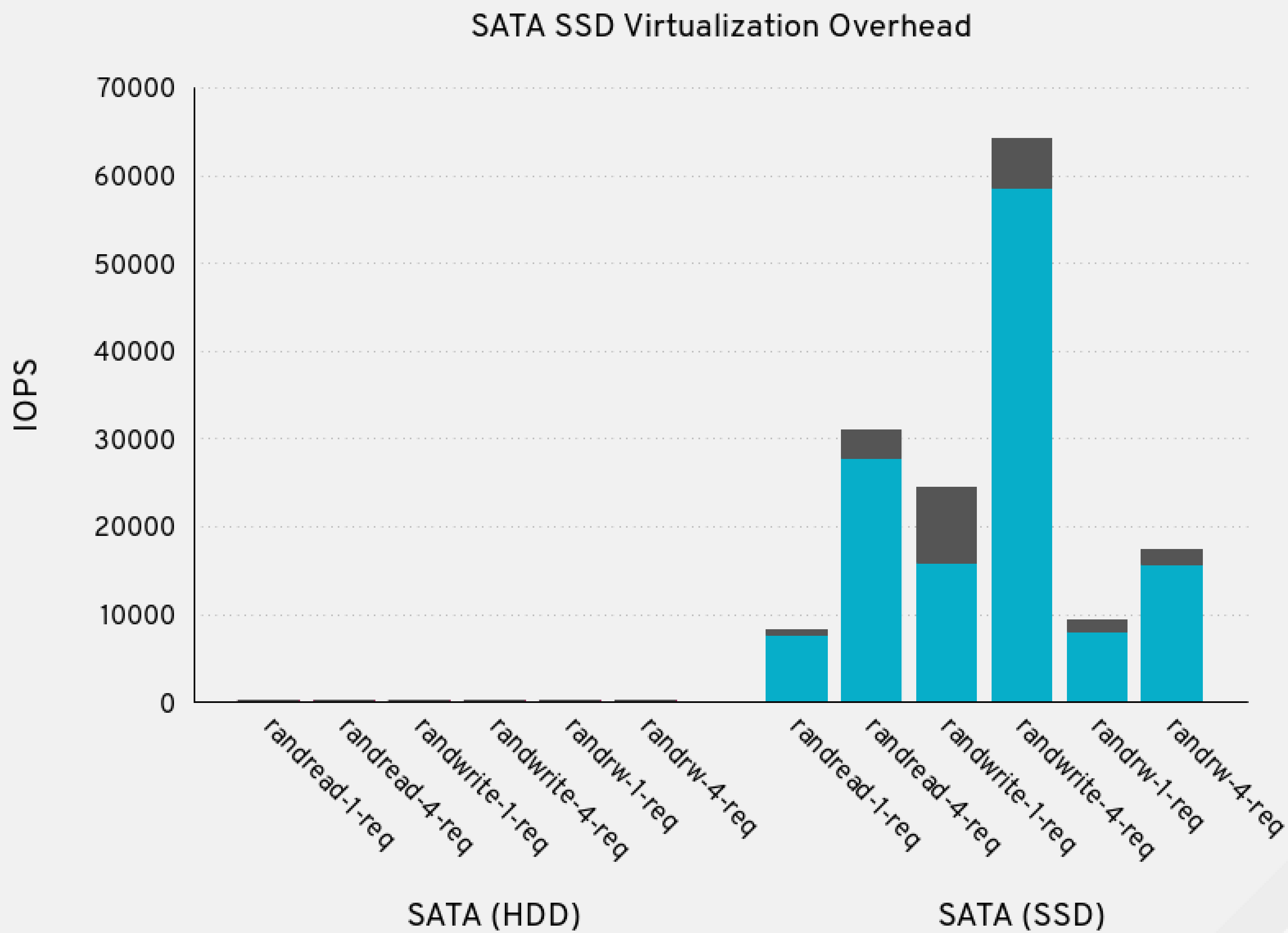
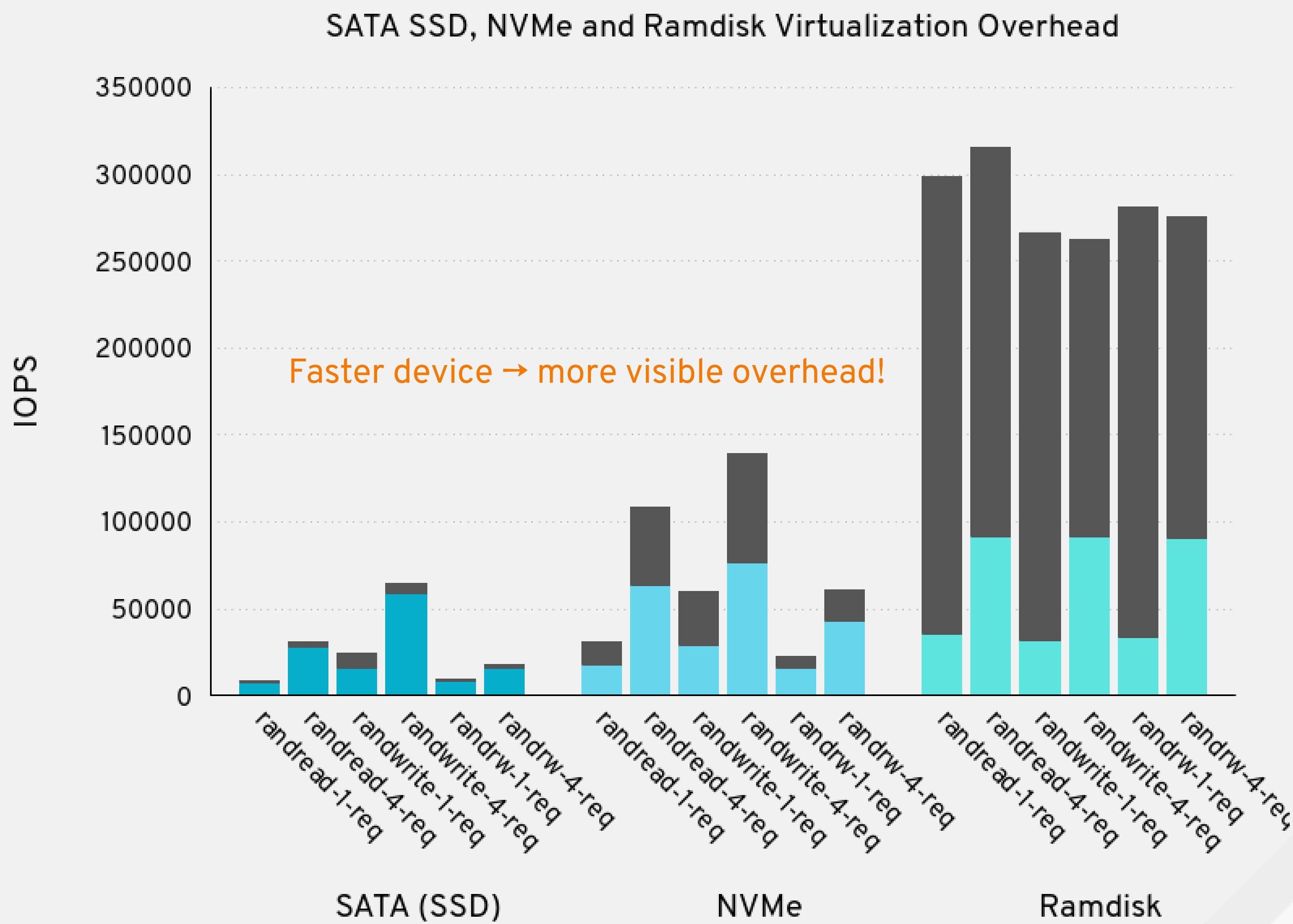
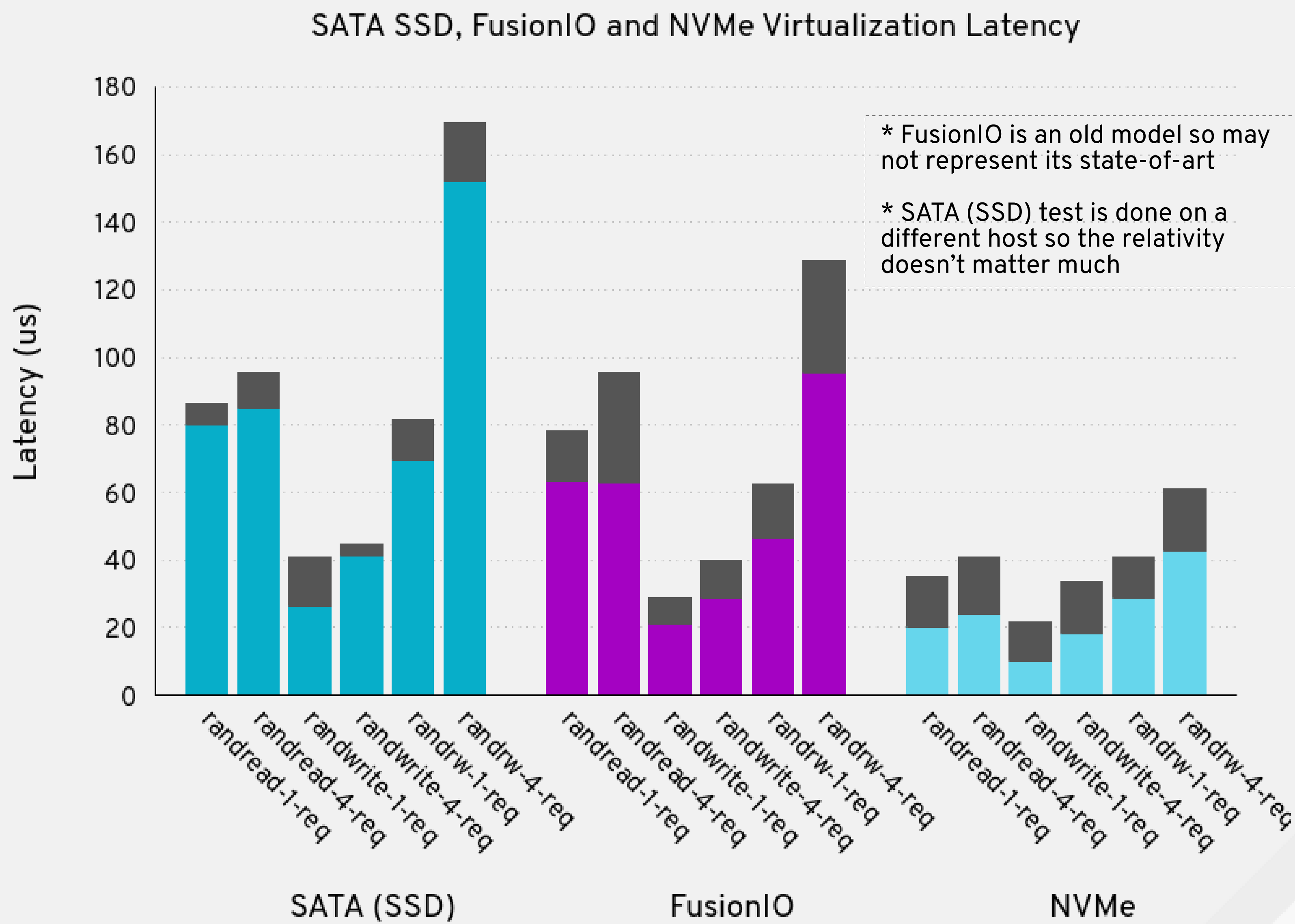
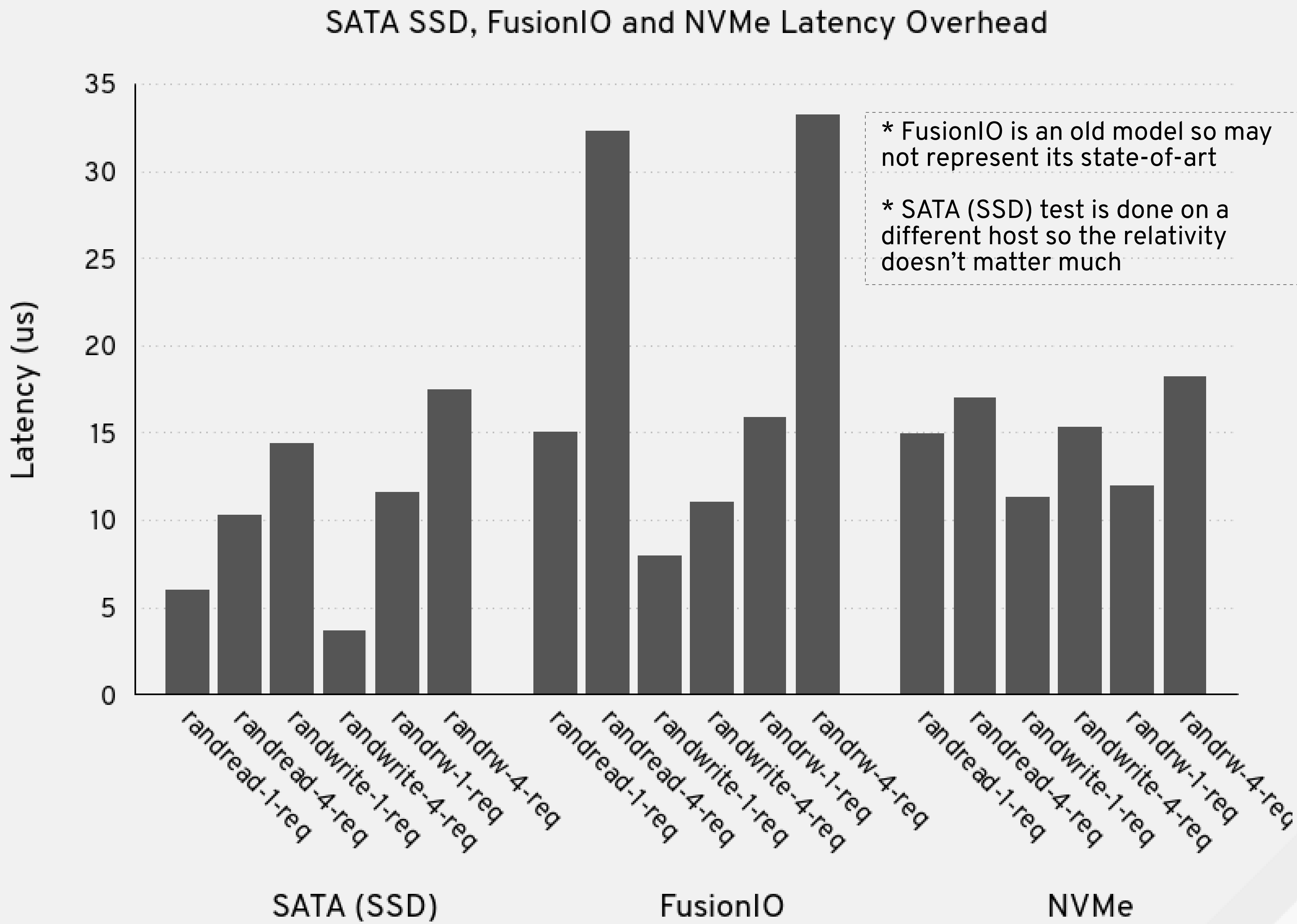

SATA HDD and SSD Performance Comparison
IOPS
70000
60000
50000
40000
30000
20000
10000
0
randread-1-req
randread-4-req
randwrite-1-req
randwrite-4-req
randrw-1-req
randrw-4-req
randread-1-req
randread-4-req
randwrite-1-req
randwrite-4-req
randrw-1-req
randrw-4-req
SATA (HDD)
SATA (SSD)



SATA SSD Virtualization Overhead
IOPS
70000
60000
50000
40000
30000
20000
10000
0
randread-1-req
randread-4-req
randwrite-1-req
randwrite-4-req
randrw-1-req
randrw-4-req
randread-1-req
randread-4-req
randwrite-1-req
randwrite-4-req
randrw-1-req
randrw-4-req
SATA (HDD)
SATA (SSD)


SATA SSD, NVMe and Ramdisk Virtualization Overhead
IOPS
350000
300000
250000
200000
150000
100000
50000
0
Faster device → more visible overhead!
randread-1-req
randread-4-req
randwrite-1-req
randwrite-4-req
randrw-1-req
randrw-4-req
SATA (SSD)
NVMe
Ramdisk


SATA SSD, FusionIO and NVMe Virtualization Latency
Latency (us)
180
160
140
120
100
80
60
40
20
0
randread-1-req
randread-4-req
randwrite-1-req
randwrite-4-req
randrw-1-req
randrw-4-req
SATA (SSD)
FusionIO
NVMe
* FusionIO is an old model so may not represent its state-of-art
* SATA (SSD) test is done on a different host so the relativity doesn't matter much


SATA SSD, FusionIO and NVMe Latency Overhead
Latency (us)
35
30
25
20
15
10
5
0
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randread-1-req
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SATA (SSD)
FusionIO
NVMe

Latency Reducing

- KVM optimizations
  - kvm_halt_poll by Paolo Bonzini
  - QEMU AioContext polling by Stefan Hajnoczi

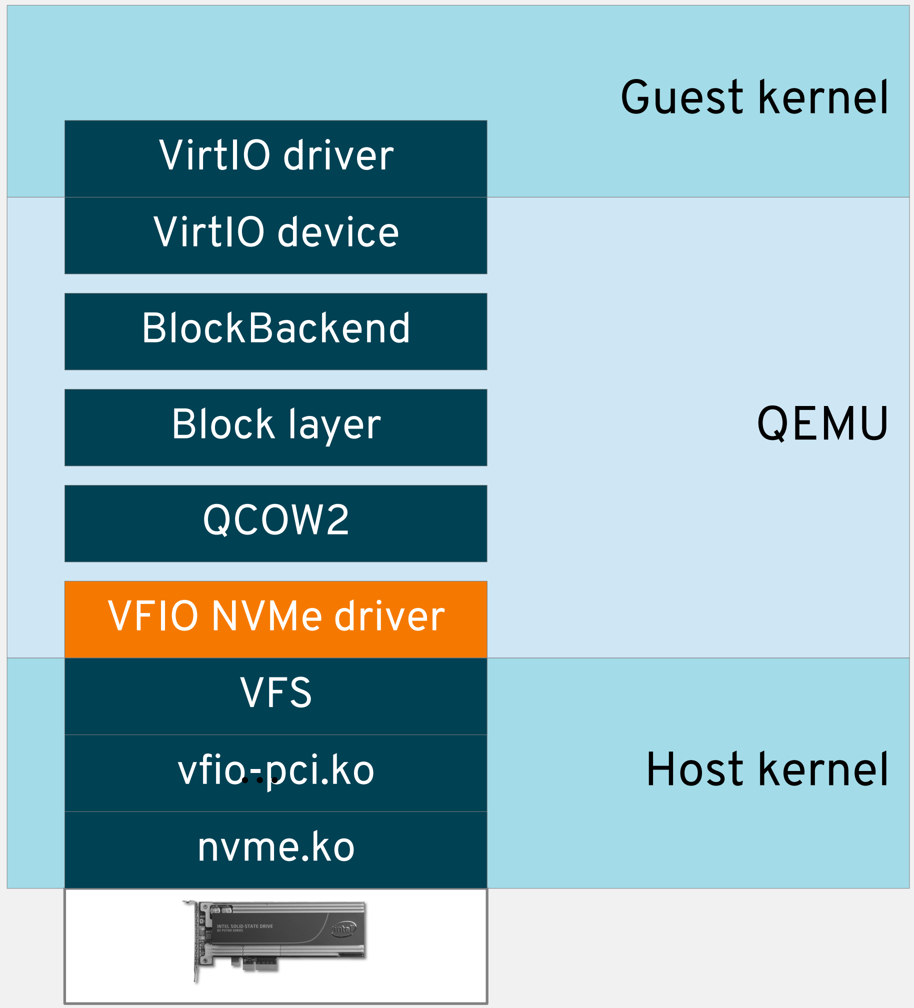
- Kernel optimizations
  - /sys/block/nvme0n1/queue/io_poll by Jens Axboe (improves aio=threads case)

- Device assignment
  - QEMU: -device vfio-pci

- Userspace device driver based on VFIO
  - DPDK/SPDK: vhost-user-blk
  - **QEMU: VFIO driver in this talk**

Architecture

From QEMU PoV



Implementation

- $QEMU_SRC/util/vfio-helpers.c
  - A generic helper library for userspace drivers
  - Manages per device IO virtual address (IOVA) space
  - Optimized for I/O operations:
    - Pre-allocate IOVA for all guest ram
    - Efficient oneshot IOVA allocation for bounce buffer I/O

- $QEMU_SRC/block/nvme.c
  - Registers a new BlockDriver (nvme://)
  - Handles NVMe logic
  - Integrates with AioContext polling
  - Prepared for QEMU multiqueue block layer

Characteristics

- Commands: READ, WRITE (with FUA), FLUSH
- IOV based (zero-copy)
- One IO queue pair for now
- More efficient for guest I/O
- Less efficient for bounce buffered I/O and utility
  - More on this later…
- Device is exclusively used by one VM similar to device assignment

I/O Request Lifecycle

virtio-*.ko	Queue virtio request (GPA/vIOVA)
↓	
virtio	Map I/O address to host address (HVA)
↓	
virtio-blk	Parse request, call blk_aio_preadv/pwritev
↓	
block layer	Call NVMe driver
↓	
NVMe driver	Send request to device

NVMe Driver Operations

(1) Check that the addresses and lengths are aligned
If not, allocate an aligned bounce buffer to do next steps

(2) Map host addresses to IOVAs

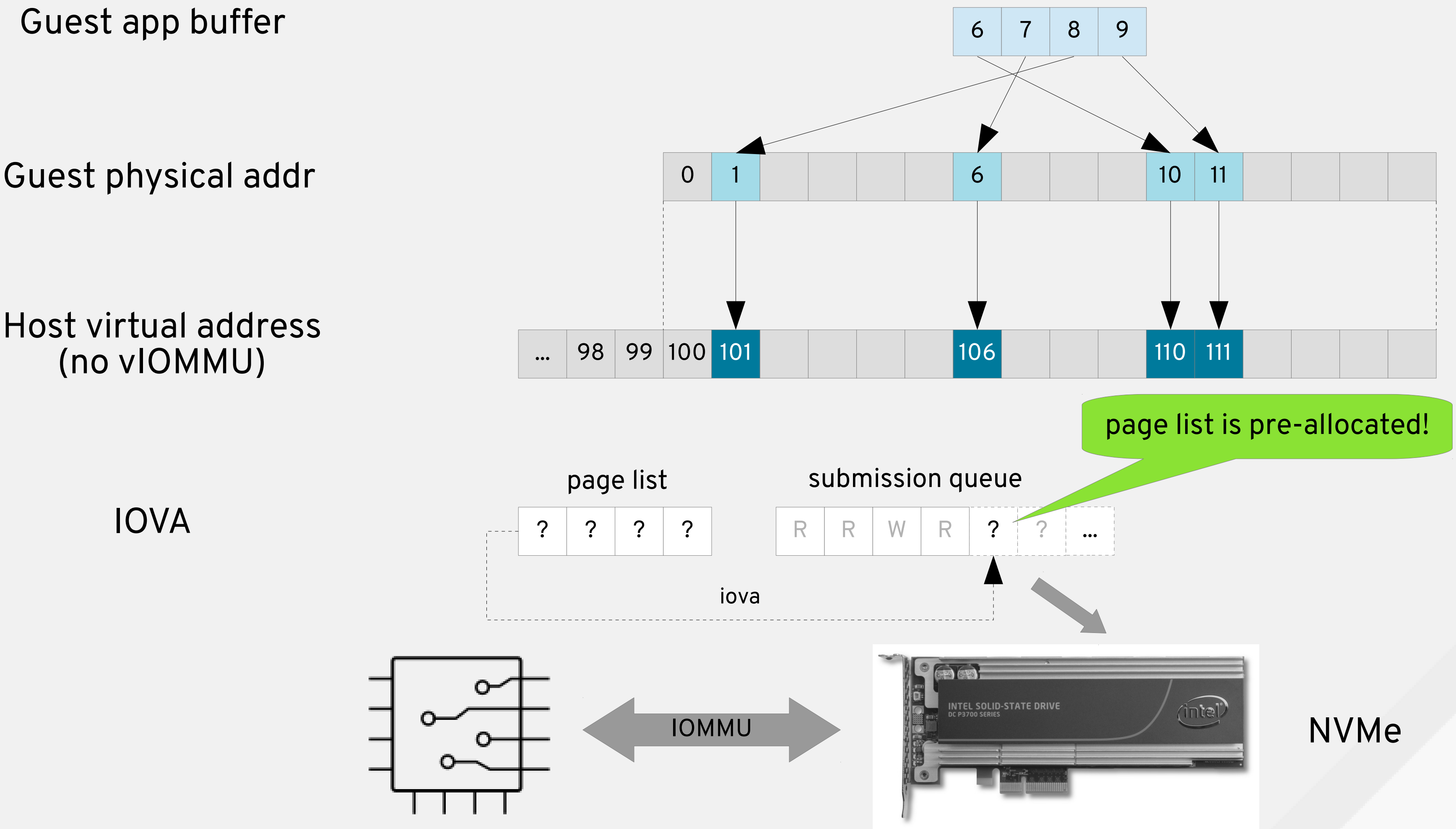
(3) Prepare an NVMe Request structure using IOVAs and put it on the NVMe I/O queue

(4) Kick device by writing to doorbell

(5) Poll for completions of earlier requests

(6) Yield until irq eventfd is readable

Address Translations



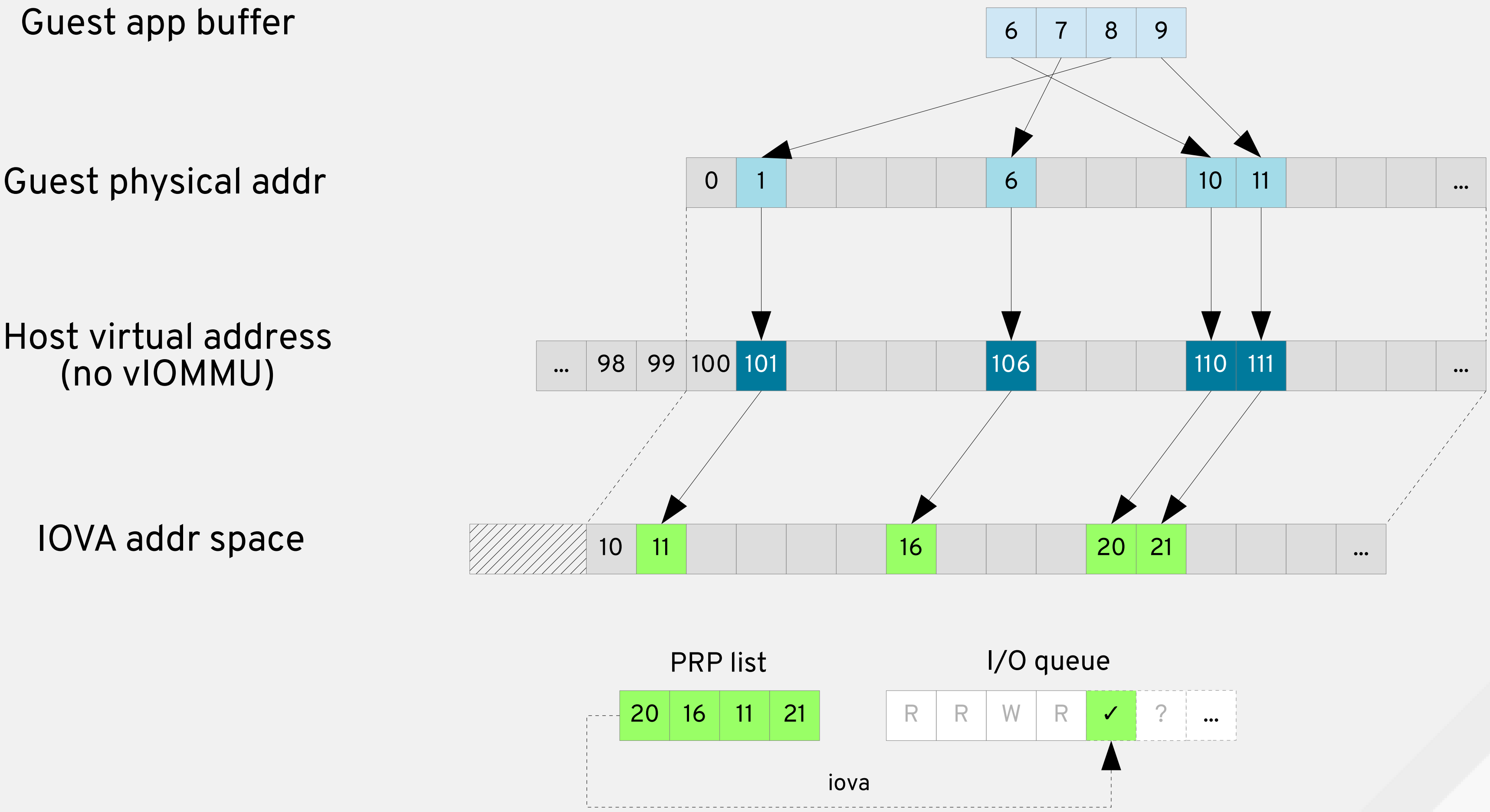
redhat.

IOVA Mapping

```
    struct vfio_iommu_type1_dma_map dma_map = {
        .argsz = sizeof(dma_map),
        .flags = VFIO_DMA_MAP_FLAG_READ |
VFIO_DMA_MAP_FLAG_WRITE,
        .vaddr = (uintptr_t)host,
        .size = size,
        .iova = iova,
    };

    ioctl(vfio_fd, VFIO_IOMMU_MAP_DMA, &dma_map);
```

Address Translations



How About Host Buffers?

- The (slow) default:
  VFIO_IOMMU_MAP_DMA each new buffer to a new address as it comes

- Remedy for hot buffers:

  ```
  void bdrv_register_buf(BlockDriverState *bs, void *host, size_t size);
  void bdrv_unregister_buf(BlockDriverState *bs, void *host);
  ```

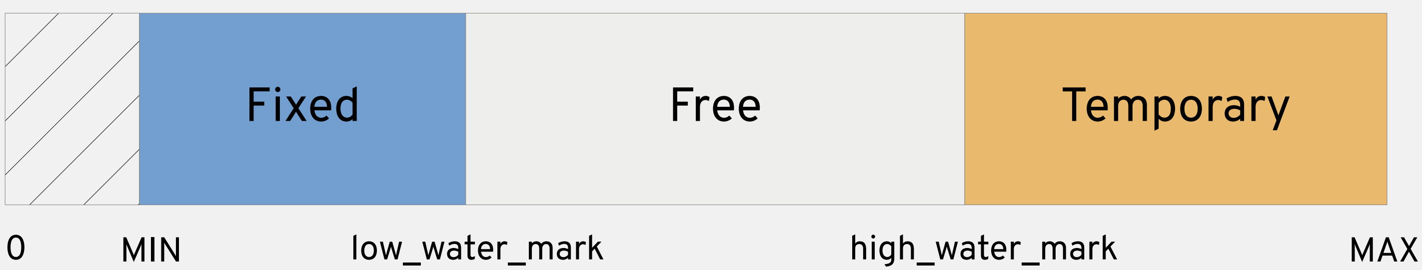
  Map/unmap a buffer to IO virtual address in the same way as guest ram.

The IOVA Allocator

- Keep record of mapped buffers for later use, if advisable
  - Distinguish throwaway / fixed mappings with a parameter

```
int qemu_vfio_dma_map(QEMUVFIOState *s, void *host, size_t size,
                      bool temporary, uint64_t *iova)
```

- Use a pair of self-incrementing counters to track available IOVAs
- When free IOVAs run out, discard all temporary mappings and reset counter (caller makes sure all old mappings are useless)



Usage

- Until patches are merged to mainline:

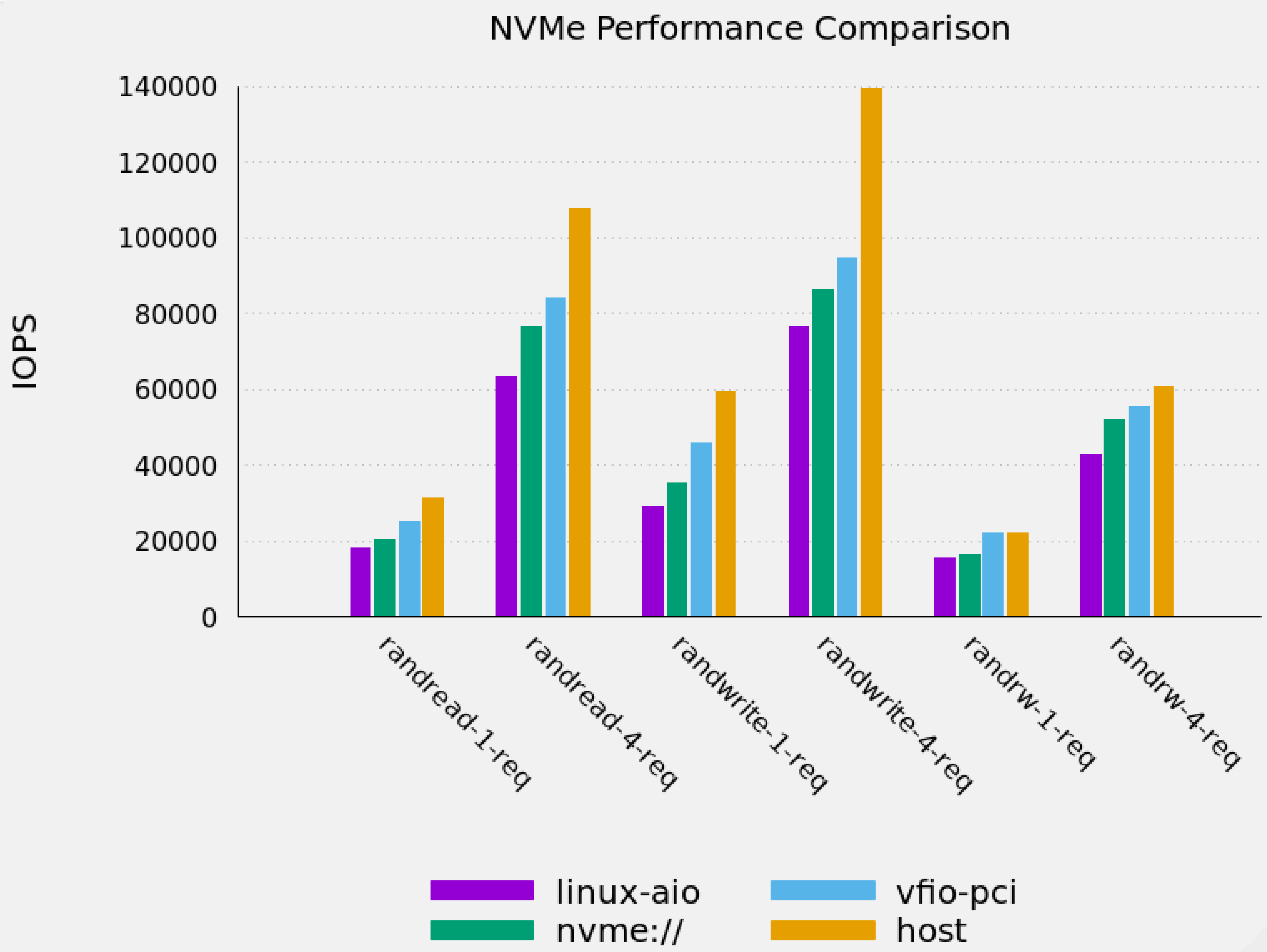
  `git clone https://github.com/qemu/famz --branch nvme`
- `configure && make`, as usual
- Bind device to vfio-pci, see also: https://www.kernel.org/doc/Documentation/vfio.txt
-
```
./x86_64-softmmu/qemu-system-x86_64 \
-enable-kvm \
… \
-drive file=nvme://0000:44:00.0/1,if=none,id=drive0 \
-device virtio-blk,drive=drive0,id=virtio0
```

- Syntax:

```
nvme://<domain:bus:dev.func>/<namespace>
```

  Or, use structured option

```
-drive \
driver=nvme,device=<domain:bus:dev.func>,namespace=<N>
,if=none...
```


NVMe Performance Comparison
IOPS
140000
120000
100000
80000
60000
40000
20000
0
randread-1-req
randread-4-req
randwrite-1-req
randwrite-4-req
randrw-1-req
randrw-4-req
linux-aio
vfio-pci
nvme://
host

IOPS Improvement over Linux-aio

(IOPS)	Relative
rand-read-1-req	+12%
rand-read-4-req	+20%
rand-write-1-req	+22%
rand-write-4-req	+12%
rand-rw-1-req	+3%
rand-rw-4-req	+22%

Configuration Limitations

Approach	Limitation
POSIX	None
nvme://	One NVMe, one VM
SPDK vhost-user-blk	* Host must use hugepages * Guest must use VirtIO
Device assignment	* One NVMe, one VM * Guest must use NVMe

Feature Availability

Approach	Host block features	QEMU block features	Migration
POSIX	✓	✓	✓
nvme://	✗	✓	✓
SPDK vhost-user-blk	✗	✗	✓
Device assignment	✗	✗	✗

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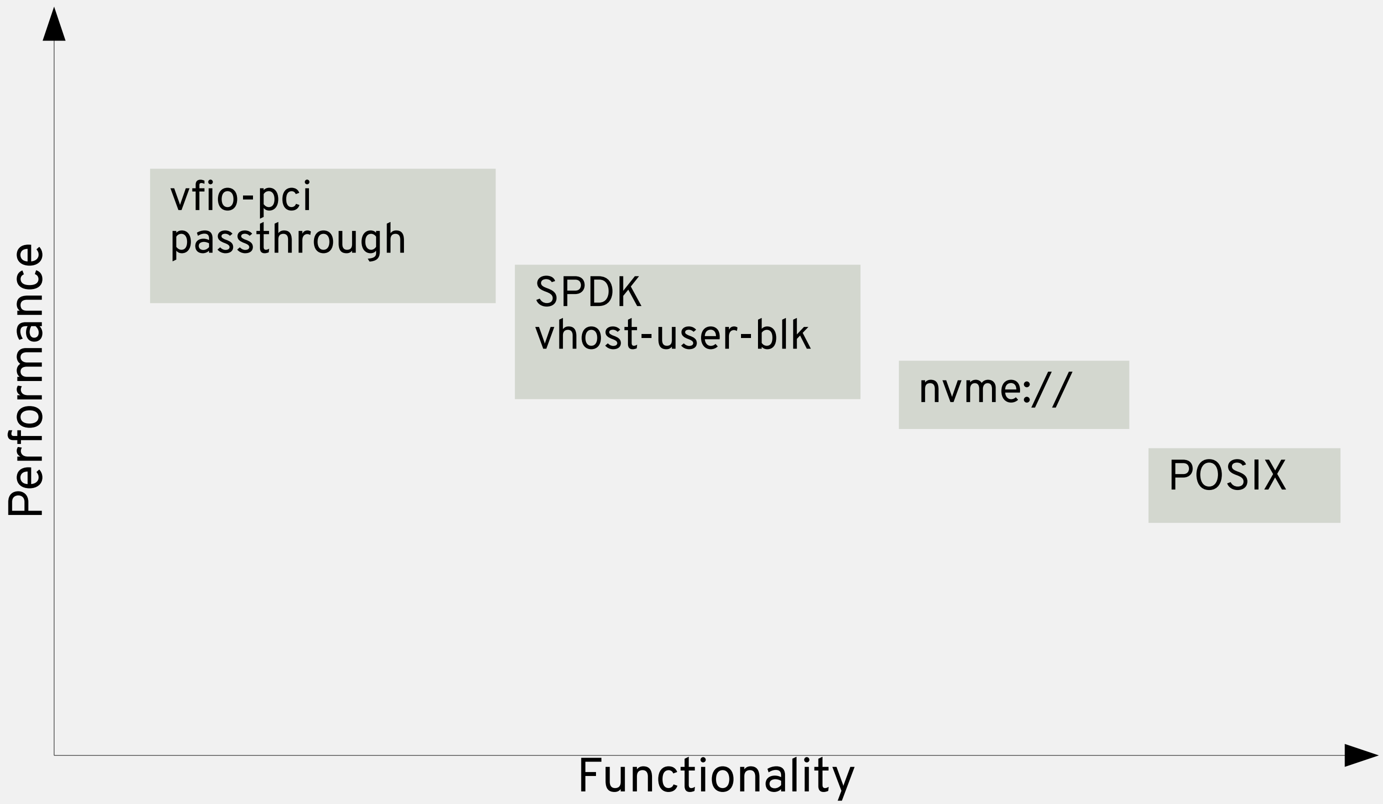
Overall comparison



Status and future

- Status
  - Patches v3 on qemu-devel@nongnu.org:
  - https://lists.gnu.org/archive/html/qemu-block/2017-07/msg00191.html
  - Also available at github:
    https://github.com/famz/qemu nvme

- TODO
  - Get it merged!
  - Integrate with multi-queue block layer

Benchmark configuration

- Host 1: Fedora 26 / RHEL 7 (x86_64)
  Intel(R) Xeon(R) CPU E5-2620 v2 @ 2.10GHz x2
  64GB ram
  Intel Corporation DC P3700 380G
  FusionIO ioDrive2 340G
  Western Digital WD RE4 WD5003ABYX 500GB 7200 RPM 64MB
- Host 2: Fedora 26
  Intel(R) Core(TM) i7-4810MQ CPU @ 2.80GHz
  16GB ram
  Samsung SSD 840 PRO 128G
- Guest: Fedora 26 (x86_64), 1 vCPU, 1GB ram
- Tool: fio-2.18
- Job:
  ramp_time = 30
  runtime = 30
  bs=4k
  rw={randread, randwrite, randrw}
  iodepth={1, 4}

THANK YOU