STORAGE DEVELOPER CONFERENCE

SDC 23

BY Developers FOR Developers

xNVMe and io_uring NVMe passthrough

What does it mean for the SPDK NVMe driver?

Simon A. F. Lund (Samsung)

Agenda

- How (and why) did SPDK start?
- SPDK’s Motivation
- Linux Storage Abstractions
- xNVMe Overview
- Performance Comparisons
- Next Steps

How (and why) did SPDK start?

Timeline: 2013

Meeting with enterprise storage company	• "We have all of these SAS SSDs in this system, but can't get all of the performance out of them."
NVMe ratified but not yet commercially available	• The performance problem was only going to get worse!
OS support for NVMe ramping quickly	• Including BSD-licensed FreeBSD drivers
Intel® Storage Group merged with division responsible for DPDK	• DPDK already tackling this same problem for network packet processing

SPDK's Motivation

- Break the software bottleneck for high-performance storage workloads
- Build an open-source community to innovate and collaborate
- Balance between ”develop new” and “optimize existing”
- Broad set of abstractions and implementations

SPDK and NVMe

Break the software bottleneck	• Performant and efficient NVMe access is priority #1!
Build an open-source community	• Collaboration with xNVMe and Linux kernel
Balance between “develop new” and “optimize existing”	• Improve SPDK’s ability to leverage Linux NVMe
Broad set of abstractions and implementations	• Enable multiple ways of accessing NVMe with SPDK

Outline

- Why
  - What do you do, when the OS storage abstractions fail?
  - What do you do, when the deployment environments fail?
- What
  - Device handles via generic and anonymous namespaces (e.g. /dev/ng0n1)
  - Device communication via io_uring command (with NVMe Passthrough)
  - SPDK Integration: xNVMe and bdev_xnvme
- Performance Comparison
- Next Steps

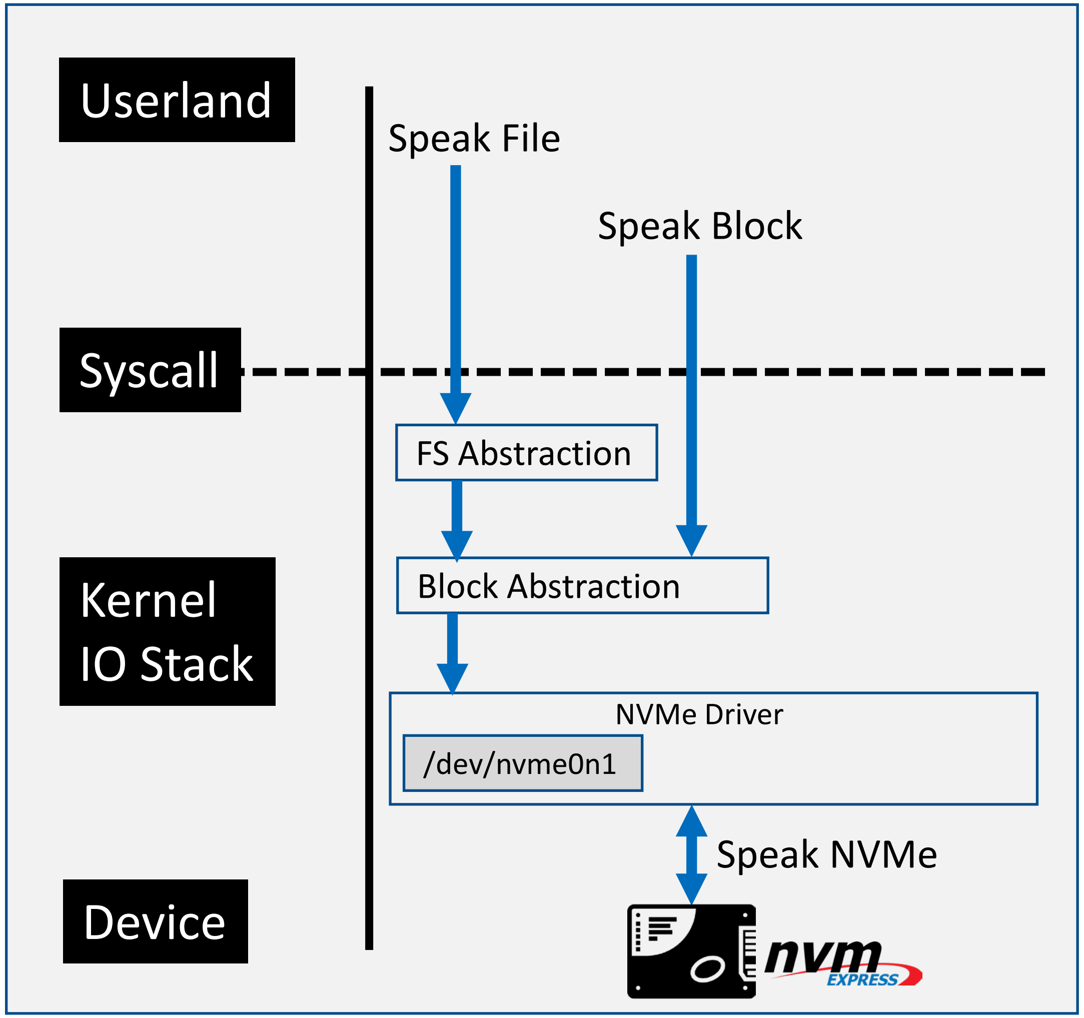
Why? 1/2

General storage abstractions

Why: storage abstractions

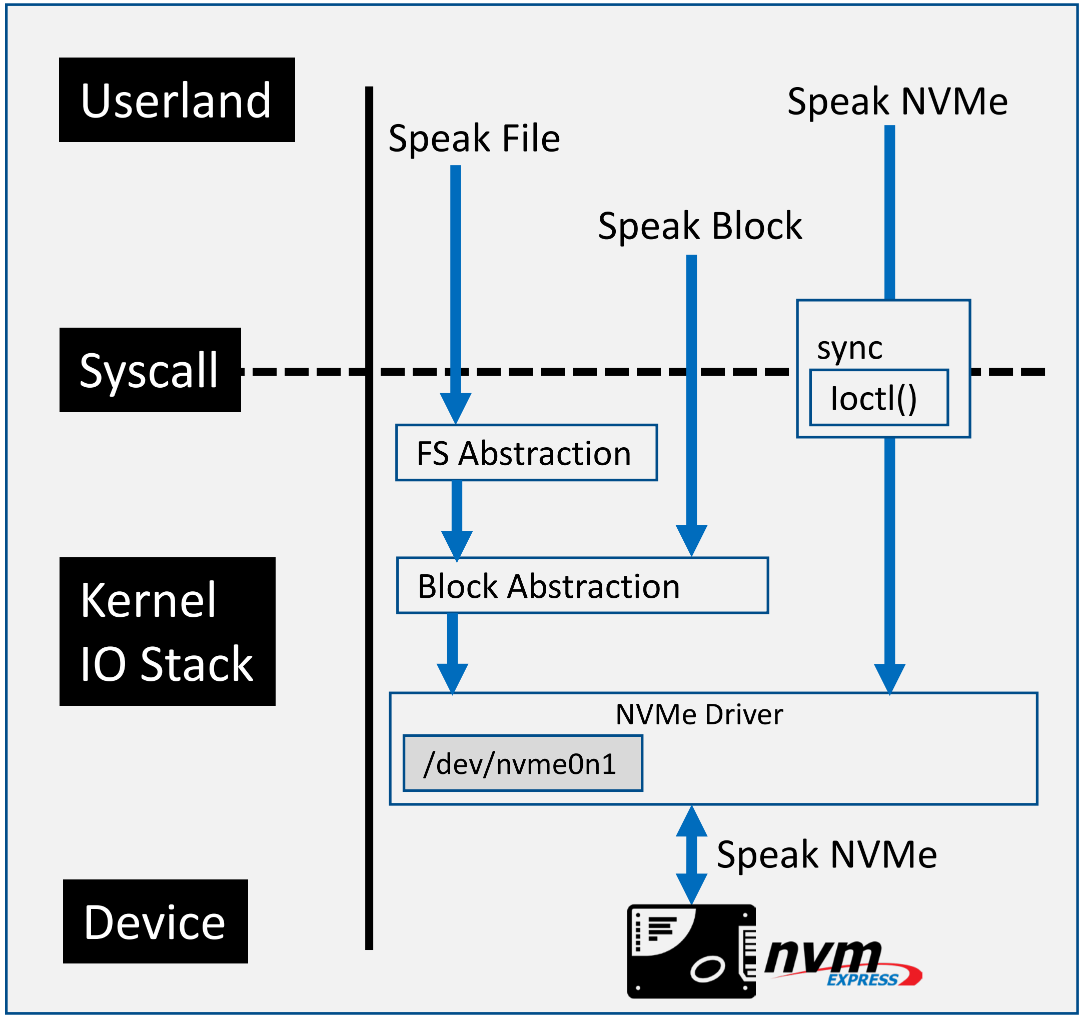
Linux

- Generic abstractions
  - Supporting a variety of devices in the same fashion
- Long-lived and well-known abstractions of blocks and files
- When/how/why do abstractions fail for NVMe?



Why: storage abstractions “speaking NVMe”

- Speaking NVMe
  - Read/write using extended LBA formats
  - Ext: directives / write_zeroes / copy
  - ZNS: mgmt. send/receive, append
  - Key-Value:
    store(k,v) / retrieve(v), list, delete, exists
  - New command-sets:
    Computational Storage



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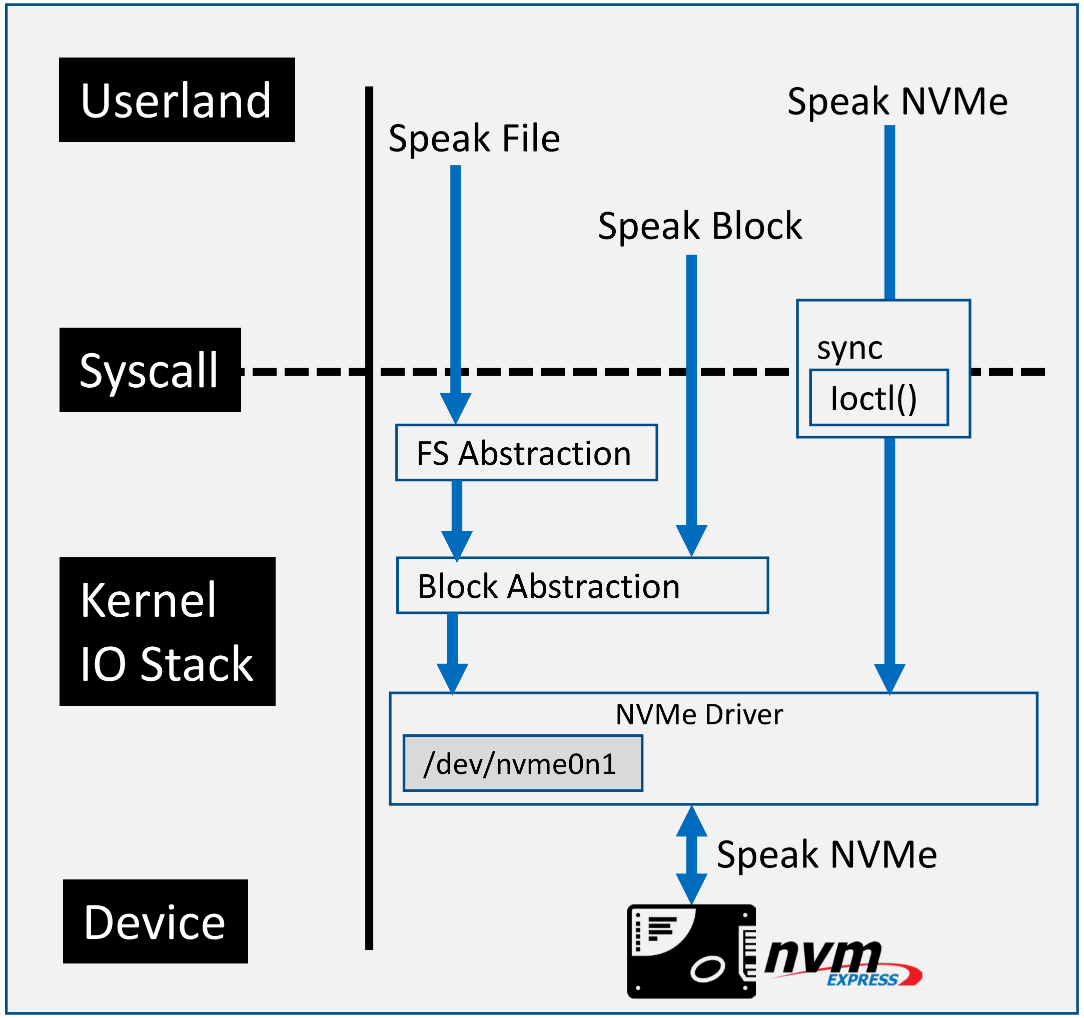
- **Abstraction failure**; must bypass
  OS abstractions to utilize devices



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Why: device handles

- Everything is a file with NVMe represented as
  - NVMe Controllers as char devices (e.g. /dev/**nvme0**)
  - NVMe Namespaces as block devices (e.g. /dev/**nvme0n1**)
    - Caveat: only for NVM and ZNS Command-Sets

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→ **Abstraction failure**; no means to get a handle to the namespace

Why: device communication

- **Efficiency** via io_uring
  - reducing the cost of crossing the border between userland and kernel
- Shared memory (rings)
  - Instead of memory-transfers
- Resource registration
  - Reduce lookup-cost
- Polling (IOPOLL | SQPOLL)
- Batching
  - One syscall ➔ multiple commands

io_uring command opcodes
IORING_OP_(READ|WRITE)V
IORING_OP_(READ|WRITE)
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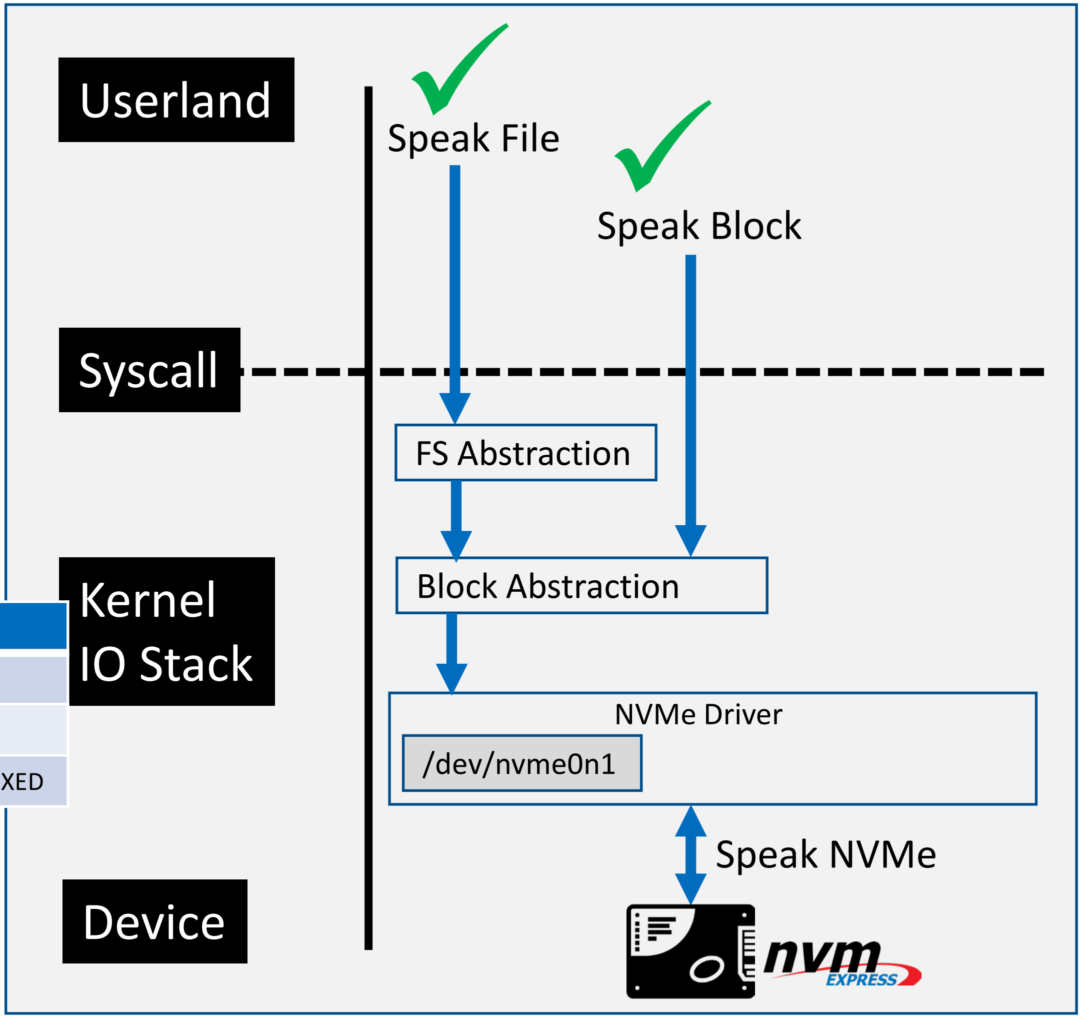

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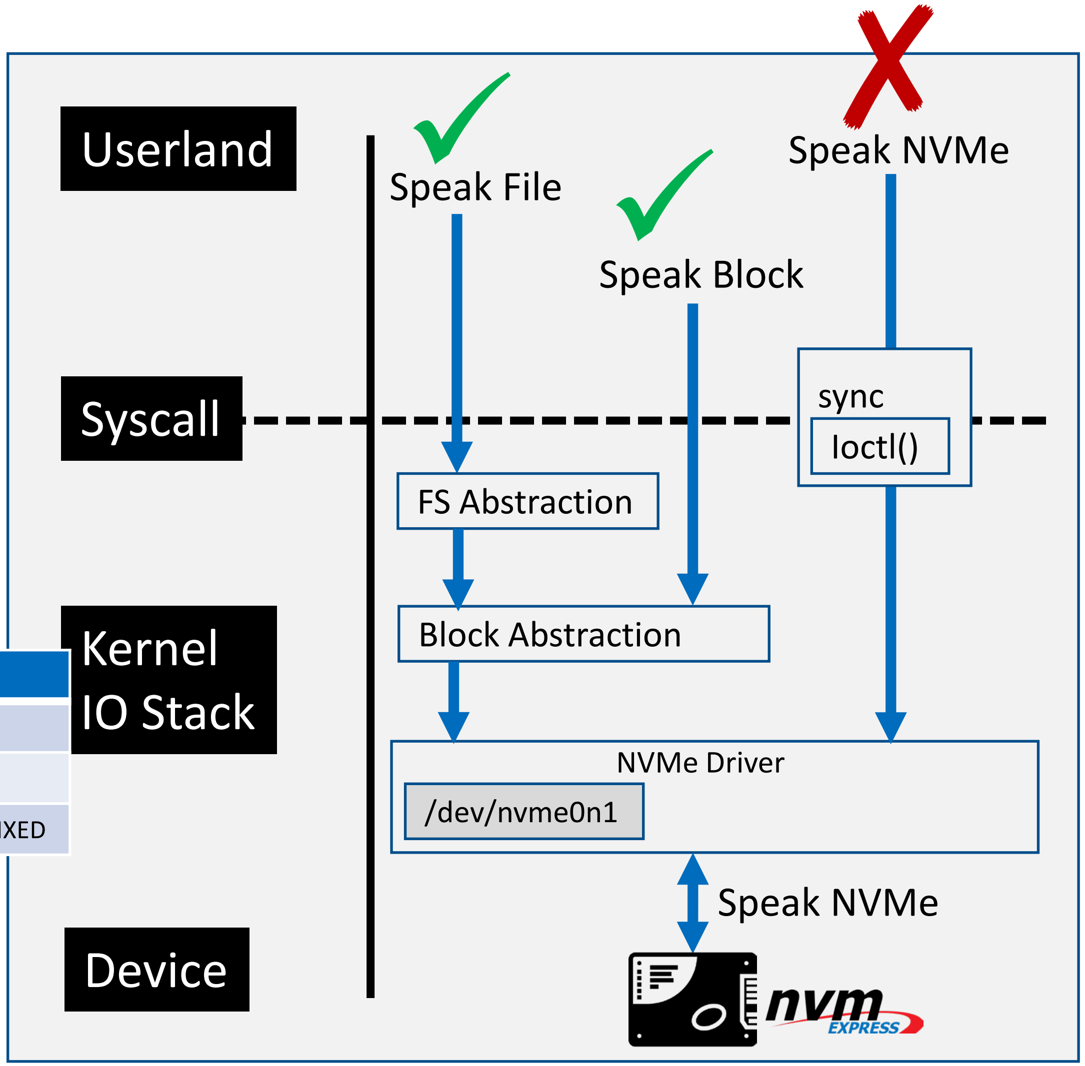

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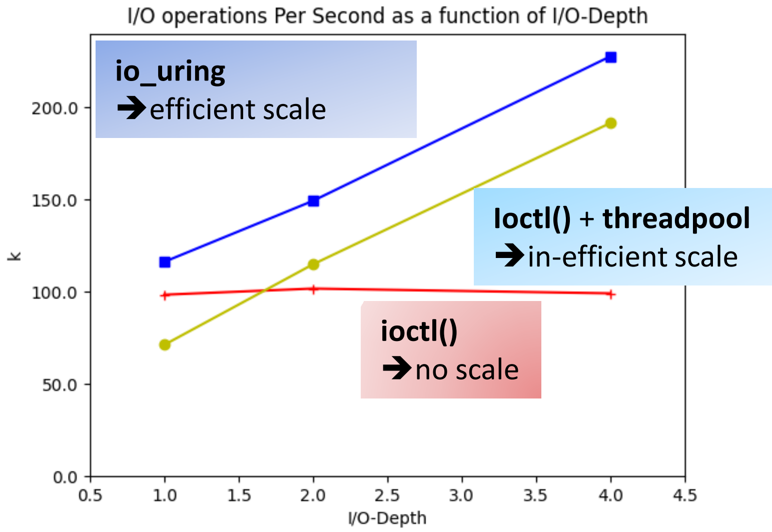

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➔**Facility**: NVMe driver ioctl()

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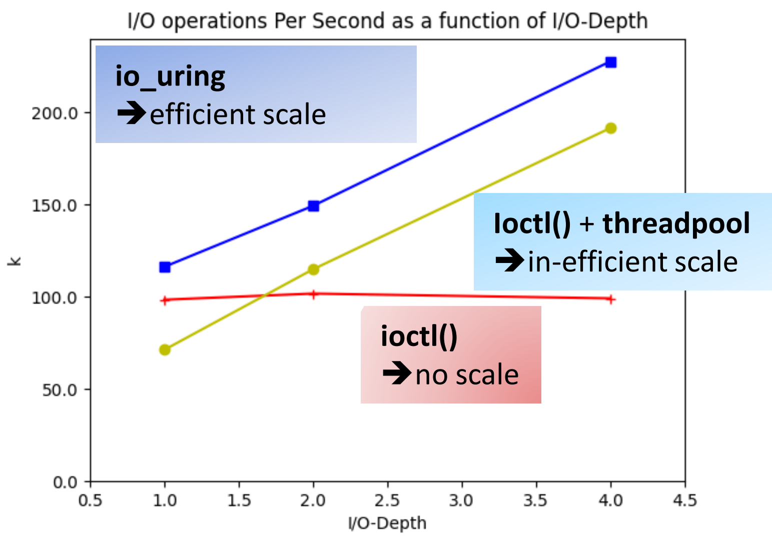

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➔**Facility**: NVMe driver ioctl()

➔**Abstraction failure**; no kernel facility to “Speak NVMe” **efficiently**

Existing solutions

- Move the storage abstraction out of the kernel and into userland

➔The SPDK Block Device abstraction (**bdev**)
➔The SPDK NVMe driver

So, when does this fail?

Why? 2/2

Deployment Environments

Why: deployment environments

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  - Unsupported IOMMU / PCIe bar address-space → binding failure

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- Deployment of SPDK Apps using the SPDK NVMe driver
  - **Requirement**: detach the Kernel NVMe driver ➔ bind to vfio-pci/uio_generic

- HW Failure
  - Other devices in the same iommu-group ➔ No detachment
  - Unsupported IOMMU / PCIe bar address-space ➔ binding failure
- Cloud failure
  - Sheer lack of NVMe devices ➔ Encapsulated storage-device-services
  - Restrictive environments

Why: io_uring **command** for SPDK?

- What do you do, when the deployment environment fails?

➔**Fallback**: operating system managed (**bdev_aio** / **bdev_uring**)

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- What do you do, when the deployment environment fails?

➔**Fallback**: operating system managed (**bdev_aio** / **bdev_uring**)

- Enable deployment of **SPDK** in environments otherwise unavailable
- Enable deployment of **SPDK** with minimal performance hit

➔**Goals** of **Linux** and **SPDK** are aligned

Why: goals for Linux

An **open-ended** representation of NVMe devices for existing and new NVMe Command-Sets with a **fast-path** for communication

Handles

➔ Bring up devices regardless of Linux device model match

Communication

➔Speak NVMe “natively”

➔Scale as efficiently as **io_uring**

➔Scale as efficiently as the SPDK NVMe Driver

What? 1/3

Generic device handles

What: a solution to handles

Handles

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- NVMe generic char interface e.g. **/dev/ng0n1**
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  - Brings up handles for namespaces with NVM and ZNS command-sets
- Command-set independence: Linux 6.0
  - Brings up handles for namespaces with **any** command-set

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Handles

- NVMe generic char interface e.g. **/dev/ng0n1**
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Device files are provided **regardless** of a matching device model, ✓
thereby enabling handles for existing and future NVMe command-sets

What? 2/3

Communication via io_uring **command** (io_uring_cmd)

What: io_uring **command**

- Generic **facility** to attach **io_uring** capabilities to a command **provider**
- Larger ring-entries embedding **commands** and their **completions**
- Command **Provider** (driver, file-system, etc.)

What: io_uring **command**

- Generic **facility** to attach **io_uring** capabilities to a command **provider**
- Larger ring-entries embedding **commands** and their **completions**
- Command **Provider** (driver, file-system, etc.)
- One such command **Provider** is the NVMe driver
  - Providing NVMe passthrough **commands**
  - **Commands** defined equivalent to NVMe driver IOCTLs
  - NVMe driver IOCTL extended with **iovec** support

note: this was a requirement enabling non-bounce-buffer utilization by the SPDK bdev abstraction

What: io_uring **command**

Handles

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Communication

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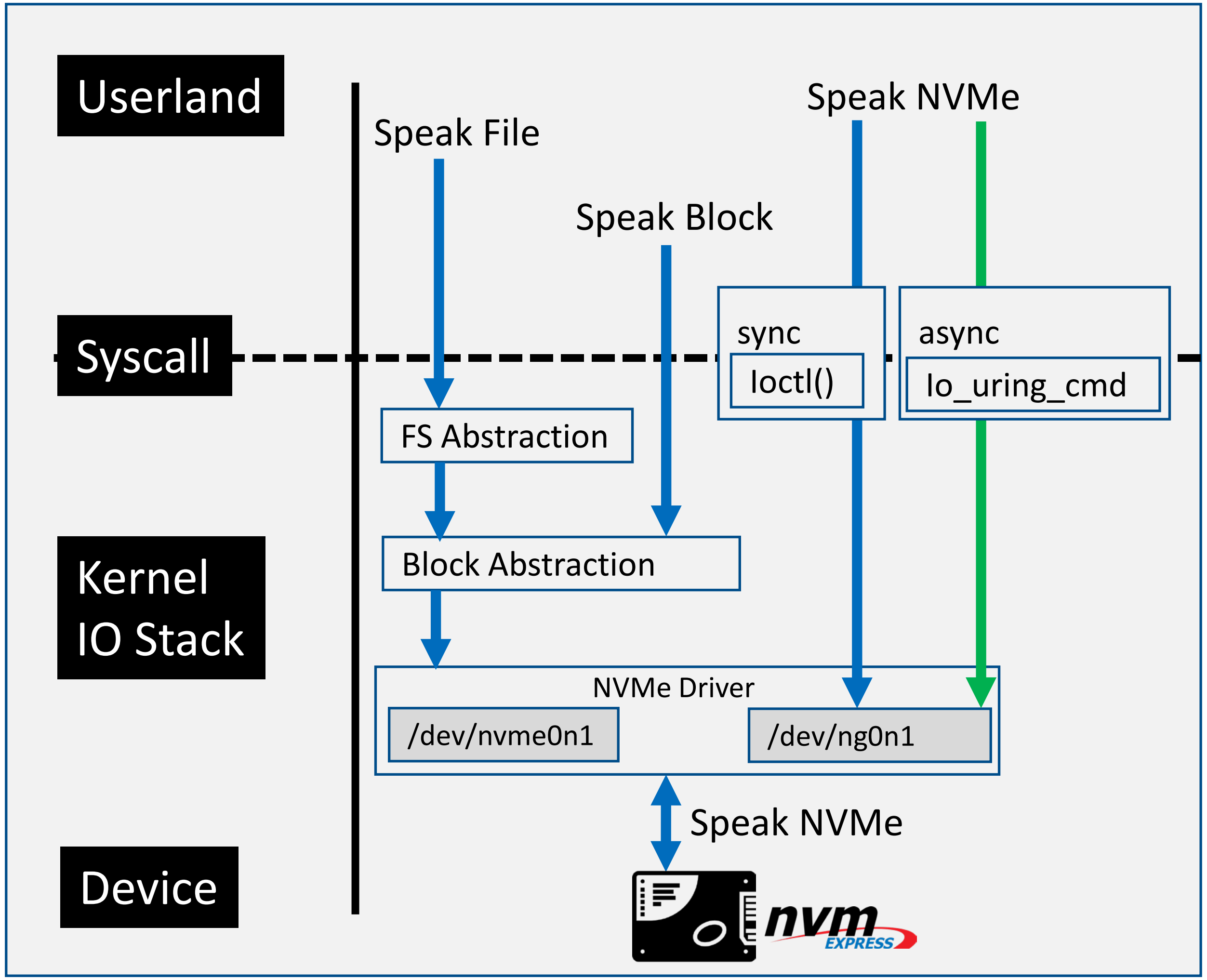
➔Scale as efficiently as io_uring?

➔Scale as efficiently as the SPDK NVMe Driver?



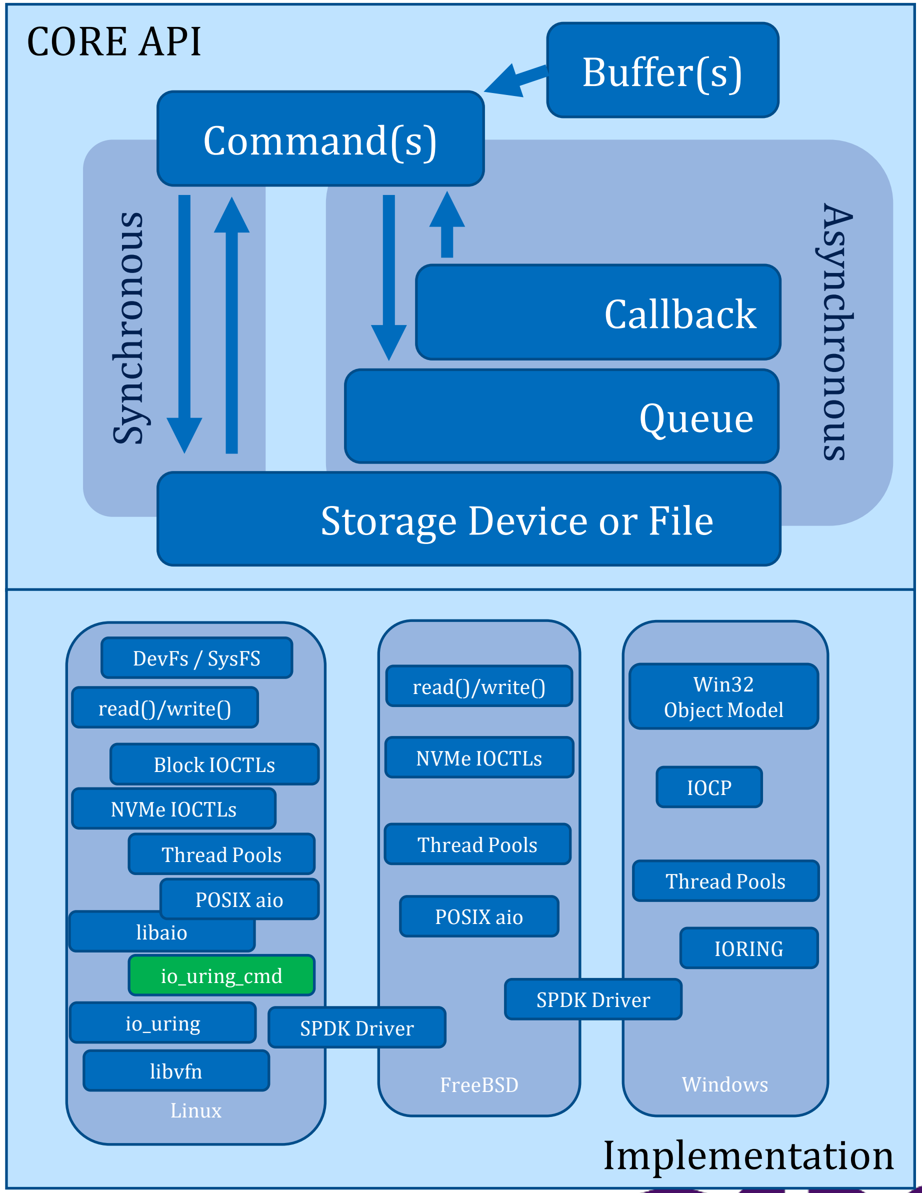
For more: see Kanchan Joshi’s Linux Plumbers Conference slides

https://lpc.events/event/16/contributions/1382/attachments/1119/2151/LPC2022_uring-passthru.pdf

What 3/3

SPDK Integration via xNVMe (bdev_xnvme)

- Core API
  - Commands and Buffers
  - Queues & Callbacks
- Command-Set Helpers
  - NVM read / write / write_zeroes / copy
  - ZNS mgmt. send / receive / append
  - KV store / retrieve / list / exists /delete
- Command-Line Tools
  - xnvme, lblk, zoned, kvs



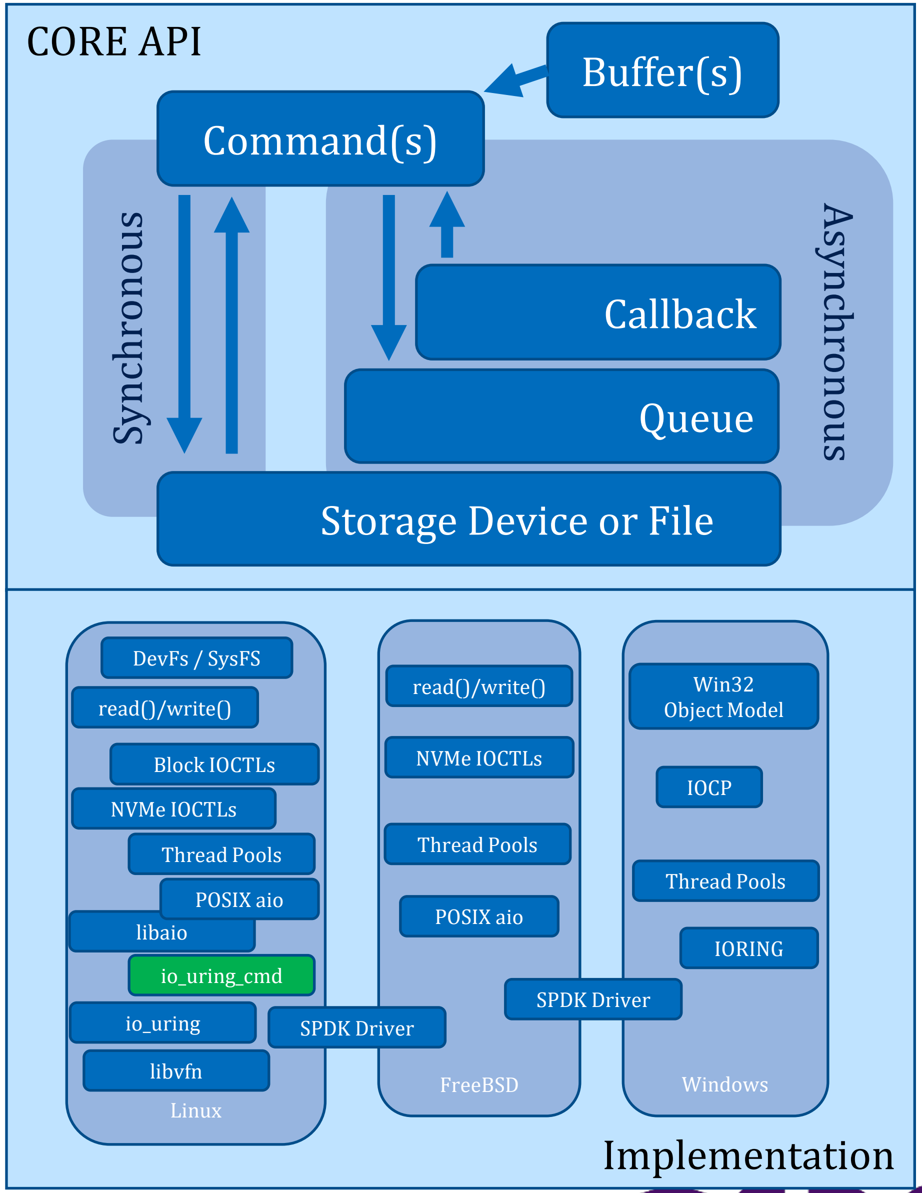
- xNVMe is used for
  - I/O interface independence
  - Minimal abstraction cost
  - Convenient command-line tools
  - Rapid experimentation via Python
- Further details

  SYSTOR22 Presentation and Paper

  https://www.youtube.com/watch?v=YoA6FVnc_pU

  https://dl.acm.org/doi/abs/10.1145/3534056.3534936

  Web: https://xnvme.io/



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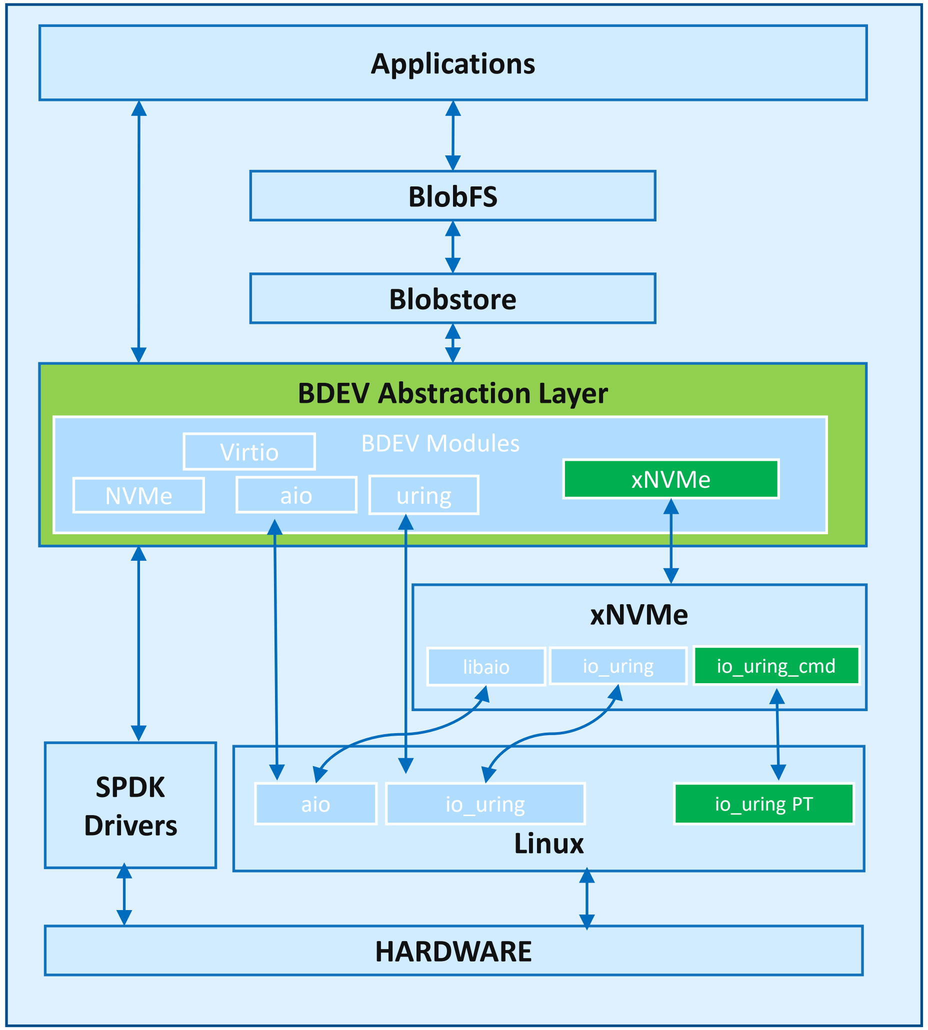
SPDK Integration: **bdev_xnvme**

- With SPDK v22.09 a new bdev module is introduced: **bdev_xnvme**
- The xNVMe bdev module calls into the core xNVMe API
- A single bdev implementation for
  - **libaio**, **io_uring**, and **io_uring_cmd**
  - Device-specific handling (zone mgmt.)
- Further details, Krishna K. Reddy
  - SDC Presentation
  https://www.youtube.com/watch?v=WbdCht6f_tU



Comparison: peak IOPS for saturated CPU

io_uring_cmd vs io_uring
io_uring_cmd vs SPDK NVMe Driver

SPDK Bdev implementations (aio, uring, xNVMe)

Comparison: system and software

- Core i5-12600, SMT **enabled**, Turbo-Boost **disabled**
  - 4x Samsung 980 Pro 1TB (512 RR ~1.0M IOPS / 4K RR 1.0M IOPS)
  - 4x Samsung 980 Pro 2TB (512 RR ~0.8M IOPS / 4K RR 0.8M IOPS)
- Device roofline **~8M IOPS** (according to spec. Sheet)
- Software
  - Linux 6.5
  - fio 3.34
  - xNVMe v0.7.1
  - SPDK v23.04 + patches for xNVMe submodule updated to v0.7.1

Comparison: system and software

- Linux Kernel version 6.5
- Debian Bullseye kernel config with the following changes
  - CONFIG_BLK_CGROUP=N
  - CONFIG_BLK_WBT_MQ=N
  - CONFIG_HZ=250
  - CONFIG_RETPOLINE=N
  - CONFIG_PAGE_TABLE_ISOLATION=N
- NVMe driver loaded with as
  - modprobe -r nvme && modprobe nvme poll_queues=1
  - /sys/block/{device}/queue/iostats set to 0
  - /sys/block/{device}/queue/nomerges set to 2
  - /sys/block/{device}/queue/wbt_lat_usec set to 0

Comparison: system and software

- Tools
  - fio: t/io_uring via "one-core-peak.sh“
  - fio: t/io_uring manually invocation
  - bdevperf
- Logs of all runs are provided for inspection and reproducibility
  - https://github.com/safl/sceb
- Also contains scripts, hw-info information, kernel-config etc.

io_uring vs. io_uring_cmd

#Devices	**Millions** of 512 byte **IOPS** via **io_uring**			
	-n=#Devices IOPOLL	-n2 -c16 –s16 IOPOLL	-n2 NOPOLL NOBATCH	-n1 SQPOLL
1	1.17	1.16	1.16	1.16
2	**2.32**	2.32	1.33	2.33
3	2.24	3.18	1.35	**2.54**
4	2.18	**4.16**	1.36	2.39
5	2.10	4.12	1.38	2.43
6	2.03	3.97	**1.39**	2.50
7	2.03	3.82	1.39	2.36
8	2.02	3.97	1.39	2.36

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5	2.09	4.35	1.38	2.42
6	2.03	4.63	**1.39**	2.49
7	2.02	**4.86**	1.38	2.51
8	2.02	4.85	1.38	2.39

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Eval: goals for Linux

An **open-ended** representation of NVMe devices for existing and new NVMe Command-Sets with a **fast-path** for communication

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Communication

➔ Speak NVMe "natively" ✓

➔ Scale as efficiently as io_uring ✓

➔ Scale as efficiently as the SPDK NVMe Driver?

Peak IOPS in Millions	
io_uring	4.16
io_uring_cmd	4.86

Comparison: IOPS via SPDK

- I/O generator
  - **bdevperf** –q 128 –o 512 –w randread –t10 <bdev_conf> -m <variations>

- Two variations
  - -m[0]; using a single core and no thread-sibling
  - -m[0,1]; using a single core and its thread-sibling
  - Equivalent comparison of SMT effect as is done by **t/io_uring**

Comparison: IOPS via SPDK

- Satures a single SMT thread

# Devices	Millions of 512 byte IOPS via the SPDK **NVMe Driver**	
	-m[0]	-m[0,8]
1	1.15	1.15
2	2.31	2.30
3	3.34	3.31
4	4.35	4.34
5	5.22	5.22
6	6.11	6.10
7	7.11	7.10
8	**7.24**	**8.08**

Comparison: IOPS via SPDK

Peak IOPS in Millions	
io_uring	4.16
io_uring_cmd	4.86
SPDK	8.08

- Why the gap?
- Generic facility
  - Does more than specialized user-space driver
  - Taps into generic kernel-infra
  - ➔ io_uring_cmd specific I/O path reduction
- Un-tapped optimizations
  - Management of DMA Mapping

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Comparison: bdev implementations

- Compare the following
  - bdev_xnvme vs bdev_uring
  - bdev_xnvme vs bdev_aio
  - bdev_xnvme with io-mechanisms: libaio / io_uring / io_uring_cmd
- Using bdevperf
  - Compare single-device qd=1 for a sense of overhead
  - Compare single-device qd=128 for a sense of scale
- Provide the data to motivating next steps for **bdev_xnvme**

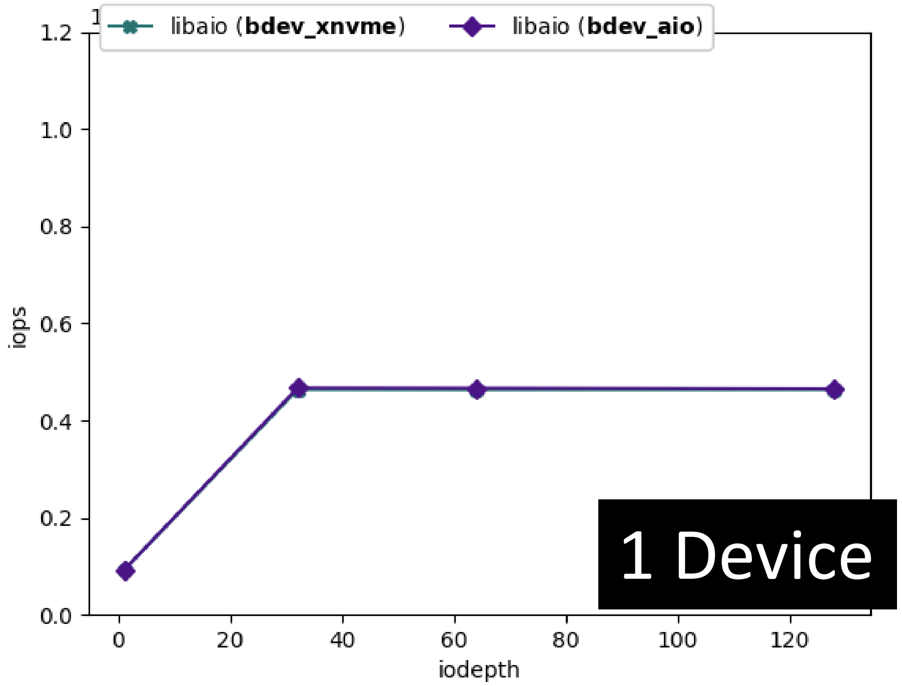
Comparison:

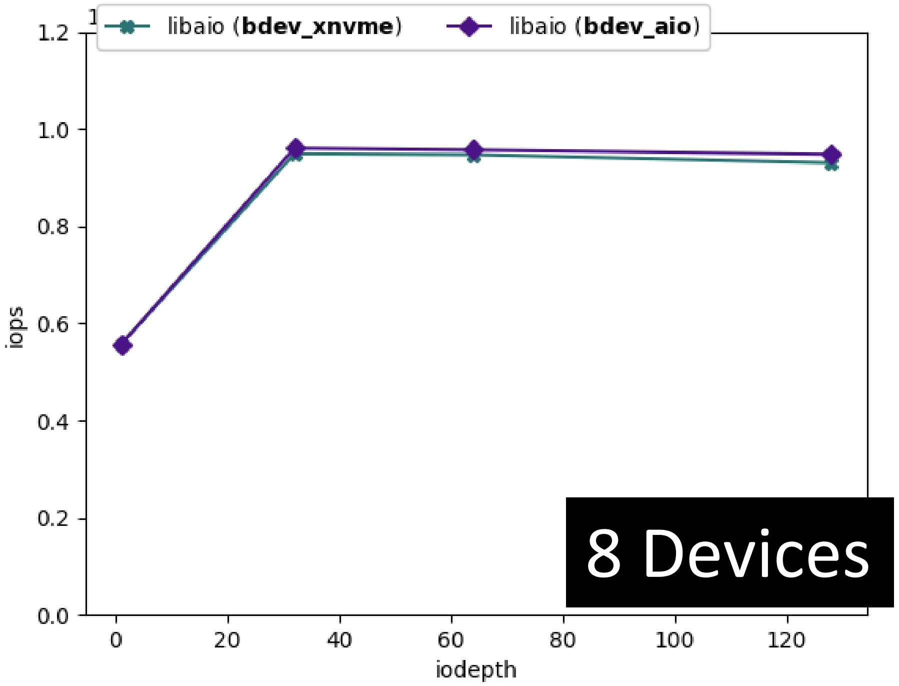
SPDK bdevs using libaio

bdev_**xnvme** vs bdev_**aio**

bdev_xnvme: {io_mechanism=libaio}

bdev_**aio** vs bdev_**xnvme**





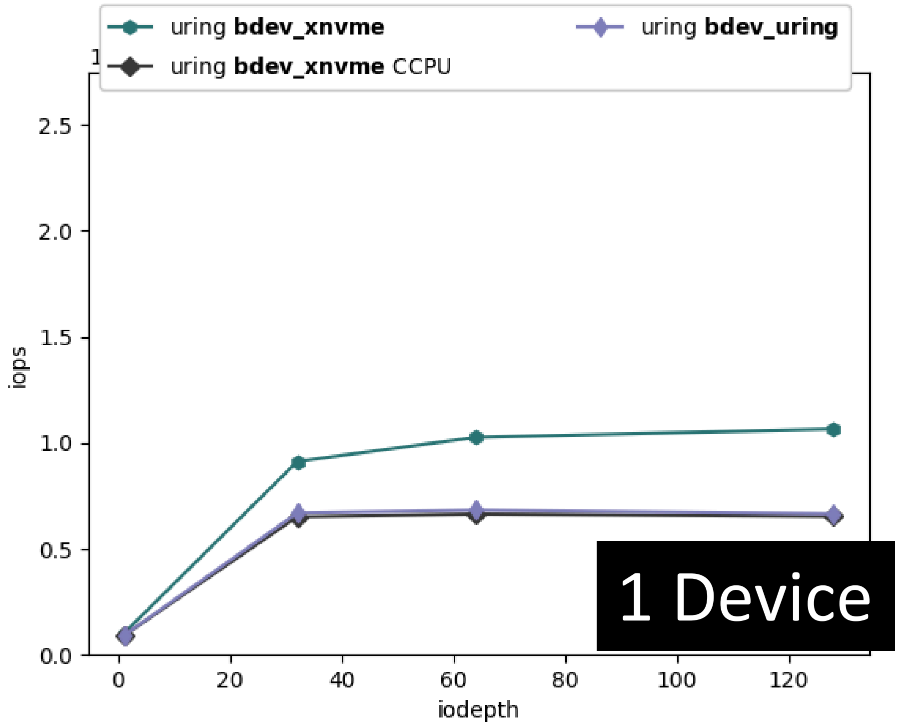
- bdev_**xnvme** at scale with bdev_**aio** ✓

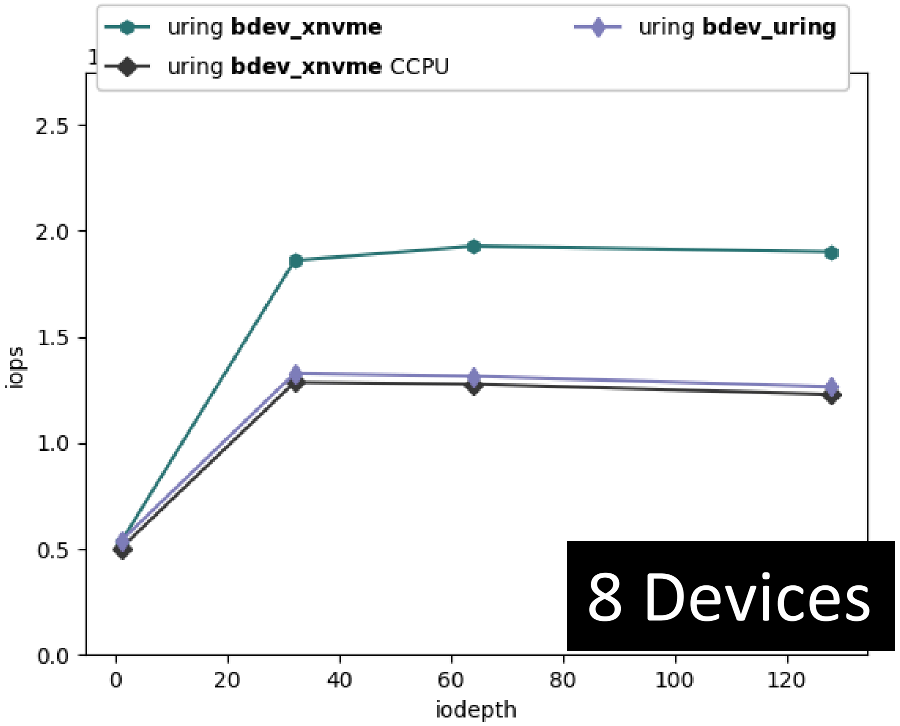
Comparison:

SPDK bdevs using io_uring

bdev_**xnvme** vs bdev_**uring**
bdev_xnvme: {io_mechanism=io_uring}

bdev_**uring** vs bdev_**xnvme**





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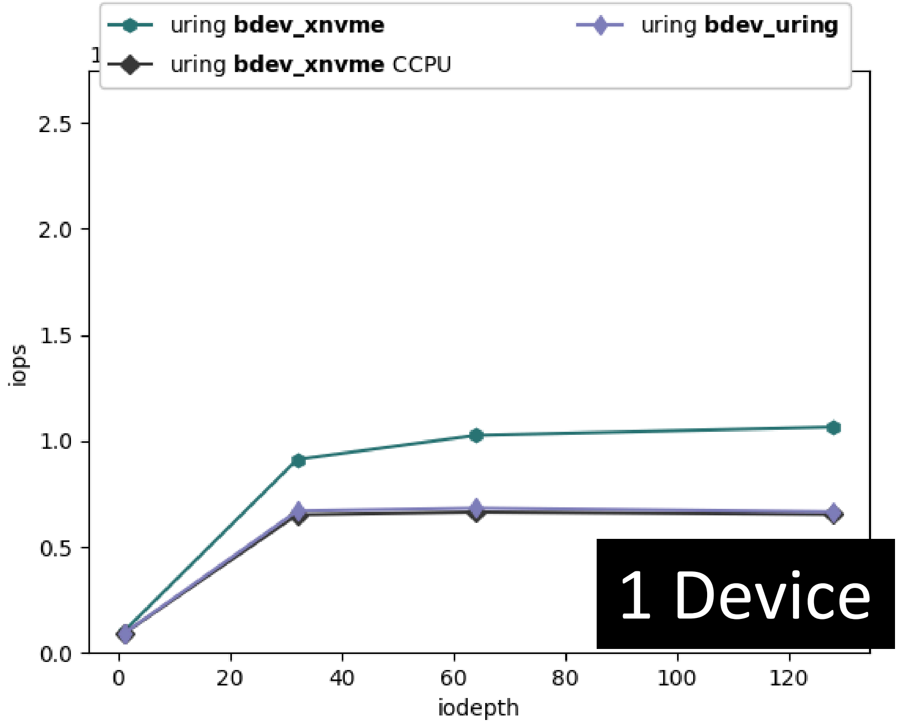
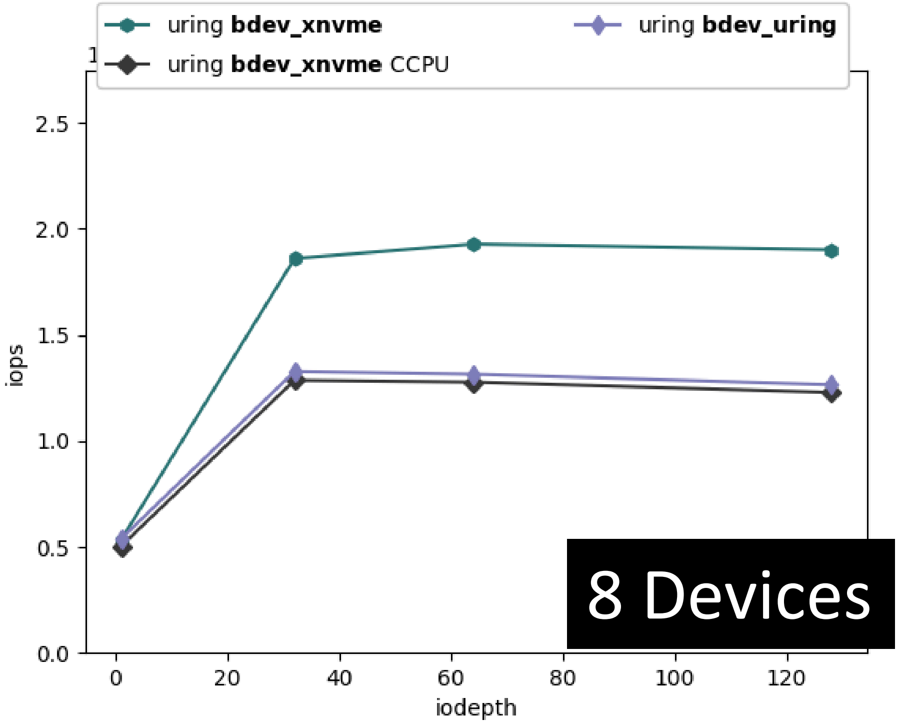
bdev_**uring** vs bdev_**xnvme**





- bdev_**xnvme** at scale with bdev_**uring**
- bdev_**xnvme** “out-scales” bdev_**uring** with **IOPOLL** enabled

Comparison:

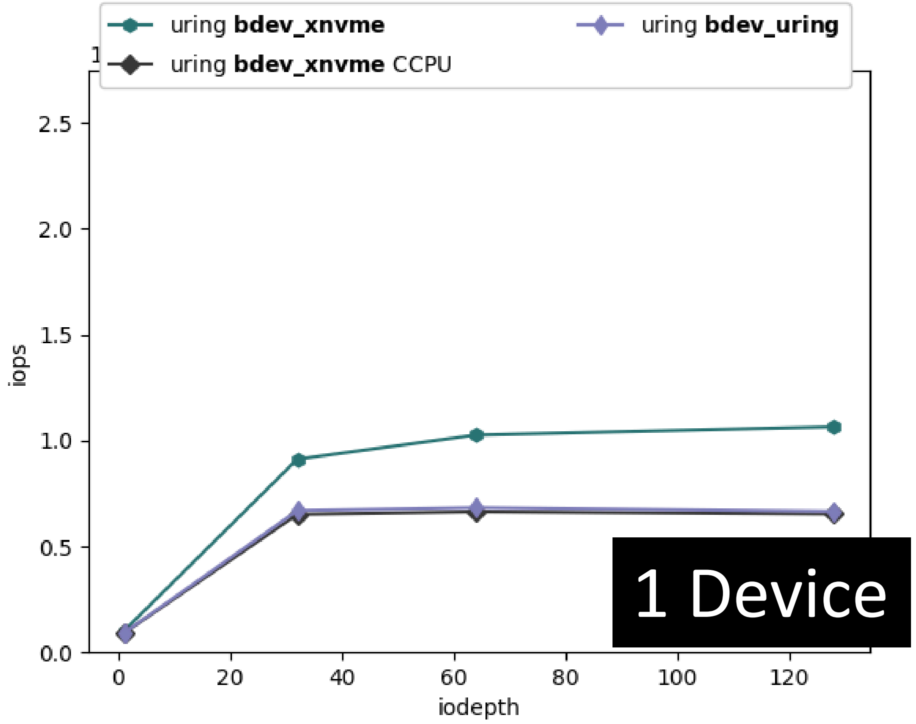
SPDK bdev using io_uring_cmd

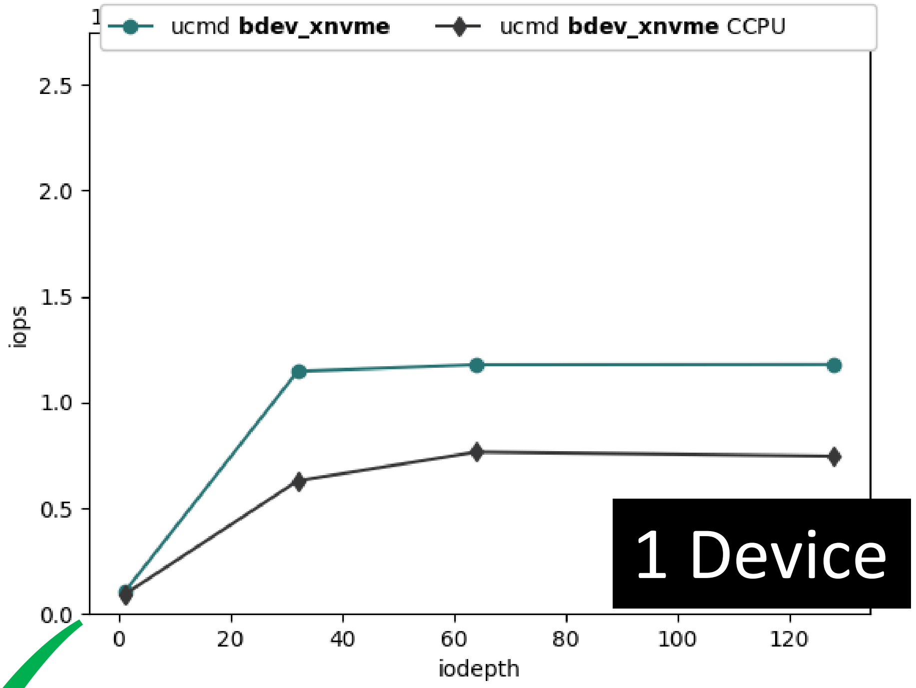
bdev_**xnvme** vs bdev_**uring**

bdev_xnvme: {io_mechanism=io_uring_cmd}

Single device

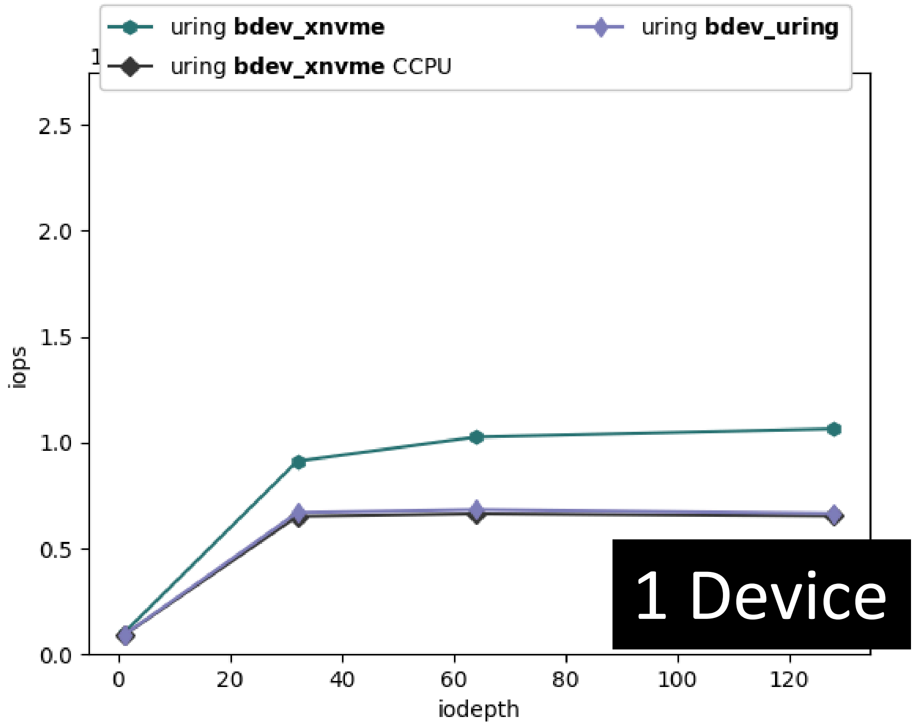
bdev_**uring** vs bdev_**xnvme**

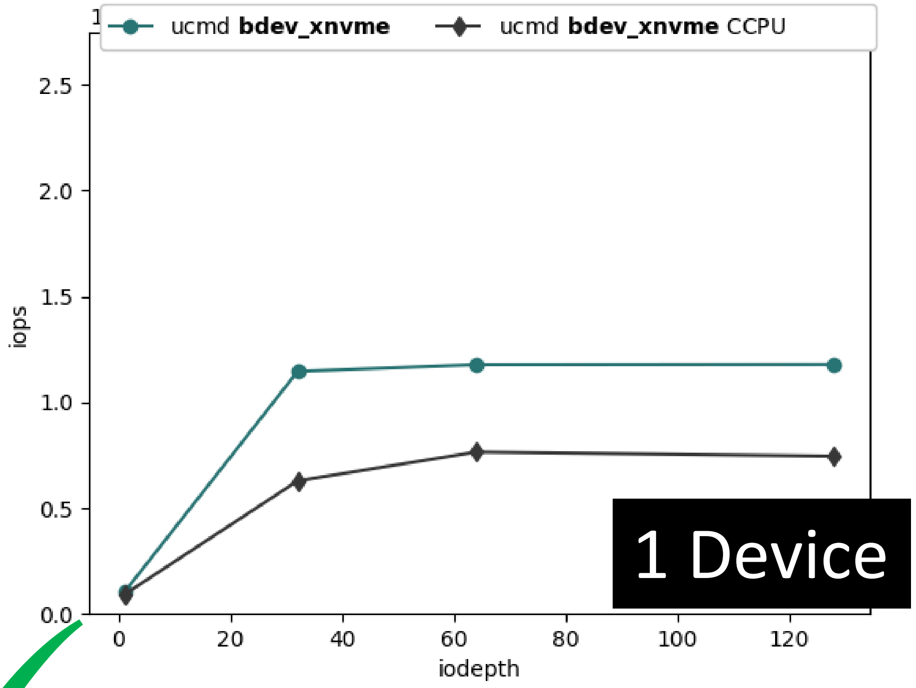




- bdev_**xnvme** (io_uring_cmd) **>** bdev_**uring** ✓

bdev_**uring** vs bdev_**xnvme**





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Comparison:

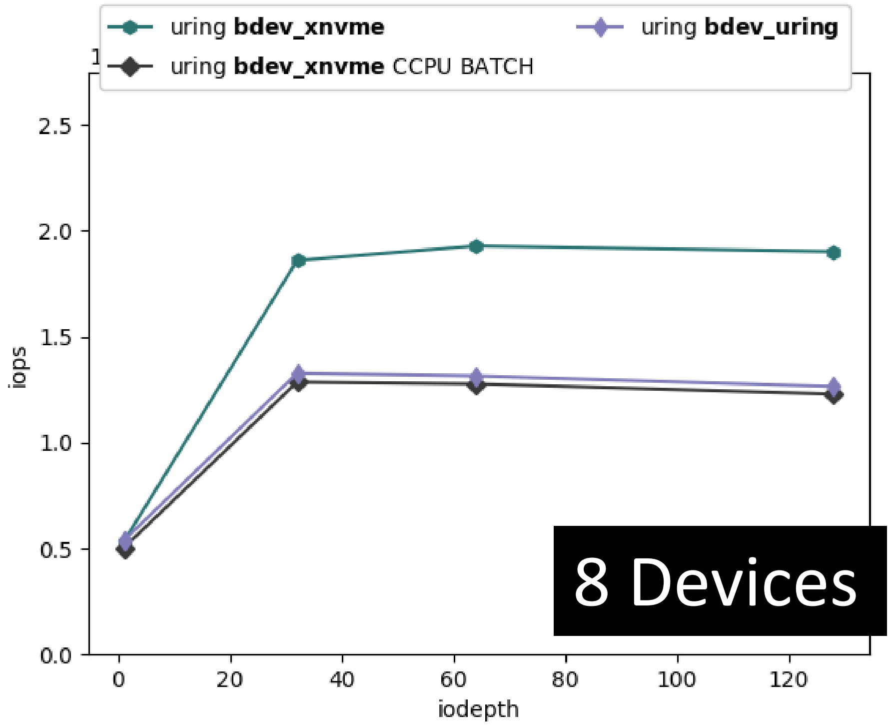
SPDK bdev using io_uring_cmd

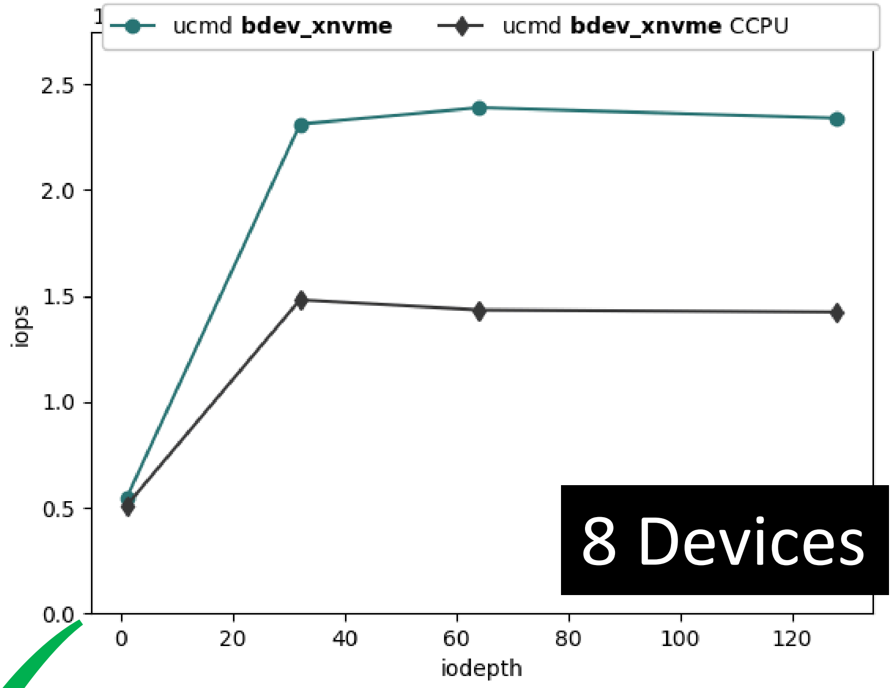
bdev_**xnvme** vs bdev_**uring**

bdev_xnvme: {io_mechanism=io_uring_cmd}

Multiple device

bdev_**uring** vs bdev_**xnvme**





- bdev_**xnvme** (io_uring_cmd) **>** bdev_**uring** ✓
  - Both with and without **IOPOLL**
- bdev_**xnvme** (io_uring_cmd) **>** bdev_**xnvme** (io_uring) ✓

What are next steps?

Next Steps: io_uring_cmd

- Handles / Encapsulation
  - I/O access-control matching file-permissions on /dev/ng*n*
  - Disable CAP_SYS_ADMIN for identify-commands (ns,ns-cs,ctrlr,ctrlr-cs,etc.)

  ➔ Enable non-root access to device information such as maximum-data-transfer-size (MDTS), device properties

- Communication
  - Investigate potentials for large-block-sizes / hugepages
  - Investigate DMA pre-mapping

Next Steps: io_uring_cmd

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Next Steps: bdev_xnvme

- Efficiency; match the IOPS rate achieved by the other **bdevs**
  - Exploring opportunities to enable batching
  - Performance “policy” e.g. “conserve_cpu” to disable optimizations
  - Otherwise: auto-enable **io_uring** optimizations where applicable and gracefully degrade in case of lacking system support
- Functionality
  - NVM commands: Write Zeroes, Flush
  - ZNS commands: (Zone Management Send/Receive)
- Deployment on Windows (**IOCP** and **IORING**)

➔ Broaden SPDK deployment while matching interface efficiency

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- ✓ Efficiency; ~~match~~ exceed the IOPS rate achieved by the other **bdevs**
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➔ Broaden SPDK deployment while matching interface efficiency

Next Steps: xNVMe

- Currently **supported** ✓
  - IORING_SETUP_{IOPOLL|SQPOLL|SINGLE_ISSUER}
  - Resource-registration (files)
  - **Batching**: done on-behalf of the user via delayed submission
- Currently **missing**
  - IORING_SETUP_{COOP|DEFER}_TASKRUN
  - Resource-registration (buffers, rings)
- General optimizations: sqe-reuse, alignment, command-construction

So, what does it mean for SPDK?

- The xNVMe **bdev** shows promise of encapsulating Linux kernel NVMe interface for the bdev abstraction
  - Single bdev to handle **libaio**, **io_uring**, and **io_uring_cmd**
  - Single bdev to handle **zone-management**
- A wider range of deployment of SPDK Applications
- Closer collaboration and integration of storage eco-systems
- What does it mean for the SPDK NVMe driver?

Thanks!

- Collaboration
  - Reproducing io_uring_cmd vs SPDK NVMe benchmarks
  - Linux Kernel io_uring_cmd optimizations
  - SPDK bdev_xnvme optimizations and functional expansion
  - xNVMe optimization and functional expansion
  - Link to previous presentation at SPDK Virtual Forum 2022
    - https://youtu.be/aYALmcP6PDU?si=H-TC_CJWgERzrd8W

- Contact
  - SPDK Slack Channels: https://spdk-team.slack.com/
  - Samsung GOST / xNVMe @ Discord: https://discord.gg/XCbBX9DmKf

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