I/O Interface Independence with **xNVMe**

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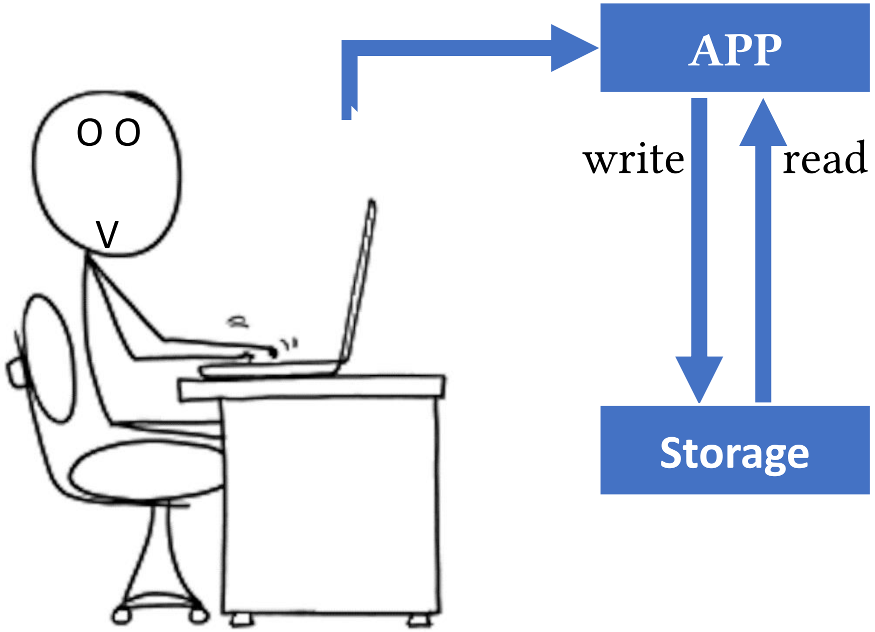
SYSTOR22

Background

Background

Traditional

- Operating System Managed
- I/O is just reading and writing
- Storage device is the bottleneck



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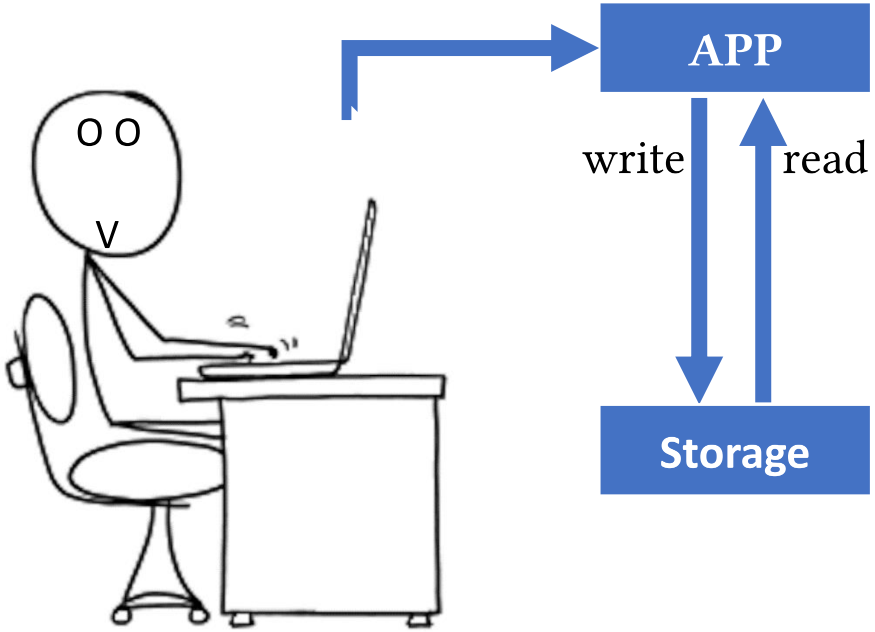
High media access latency

Did **not** benefit from parallel access



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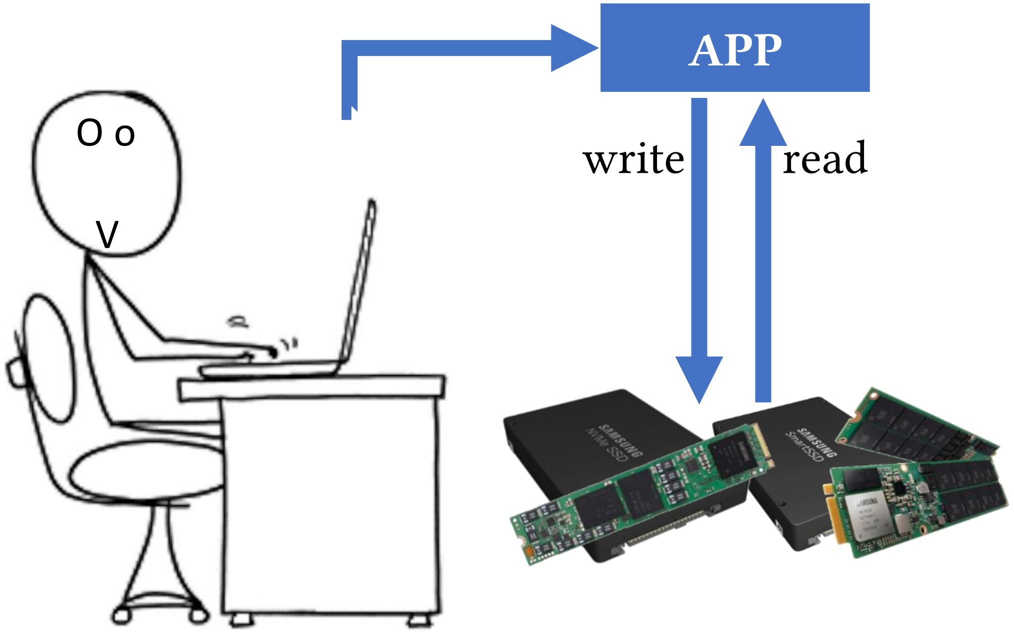

Background

Traditional + NVMe → Low media access latency → High parallel access benefit

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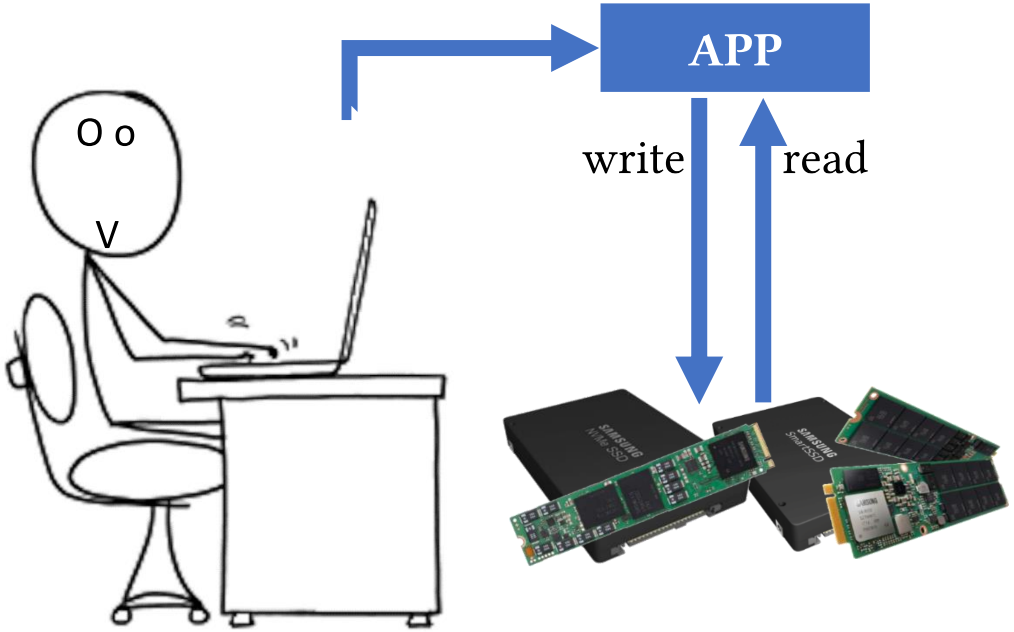

Background

Reduce the cost of crossing the address-space boundary;
system-call overhead, context-switching and memory mapping

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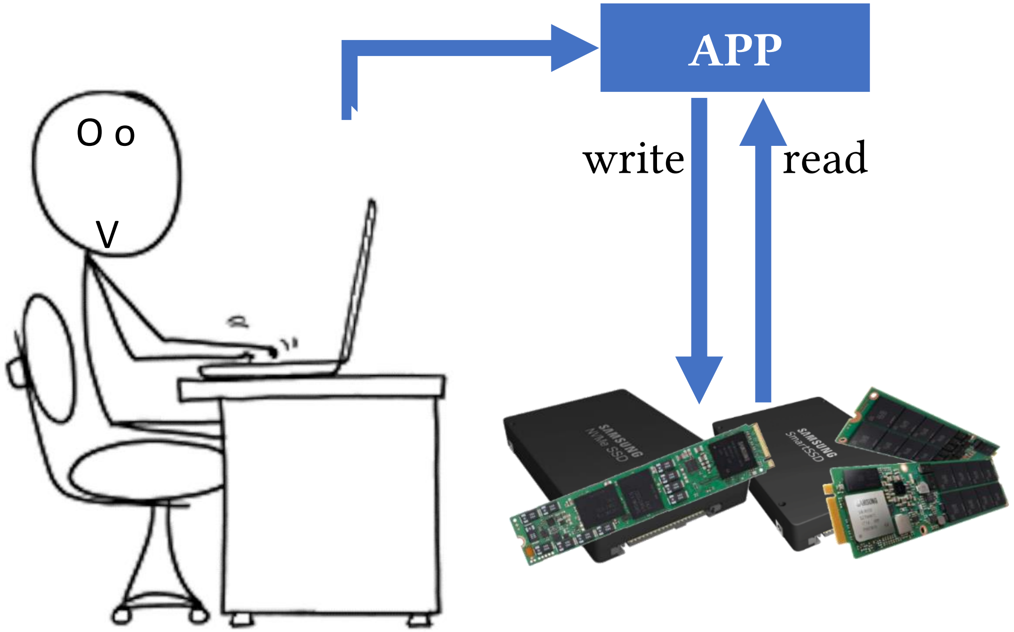

User Space

read()/write()
pread()/pwrite()
readv()/writev()

Kernel Space

vfs

Block Layer

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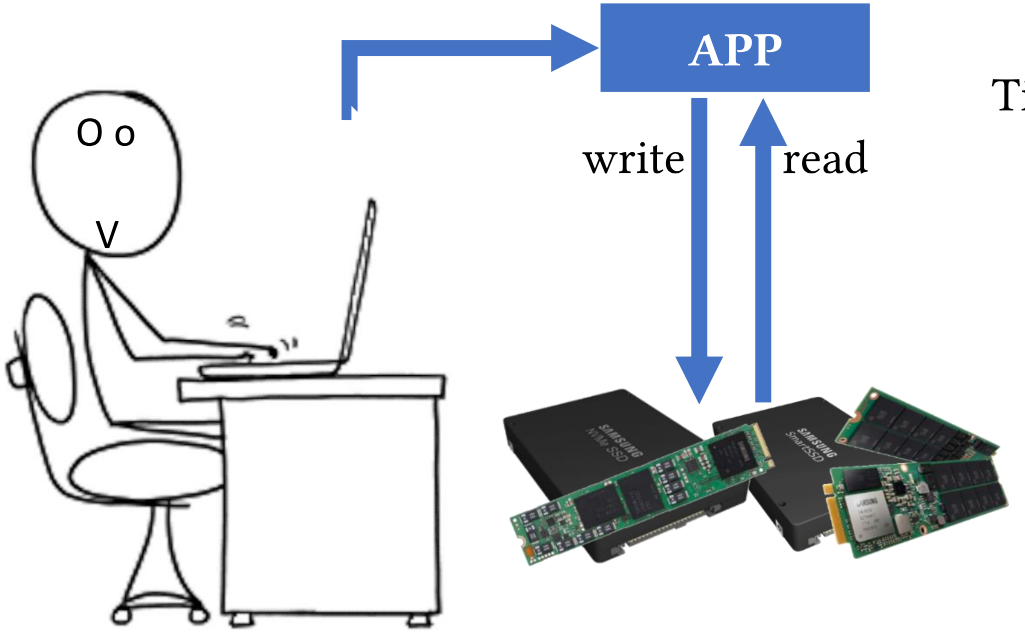
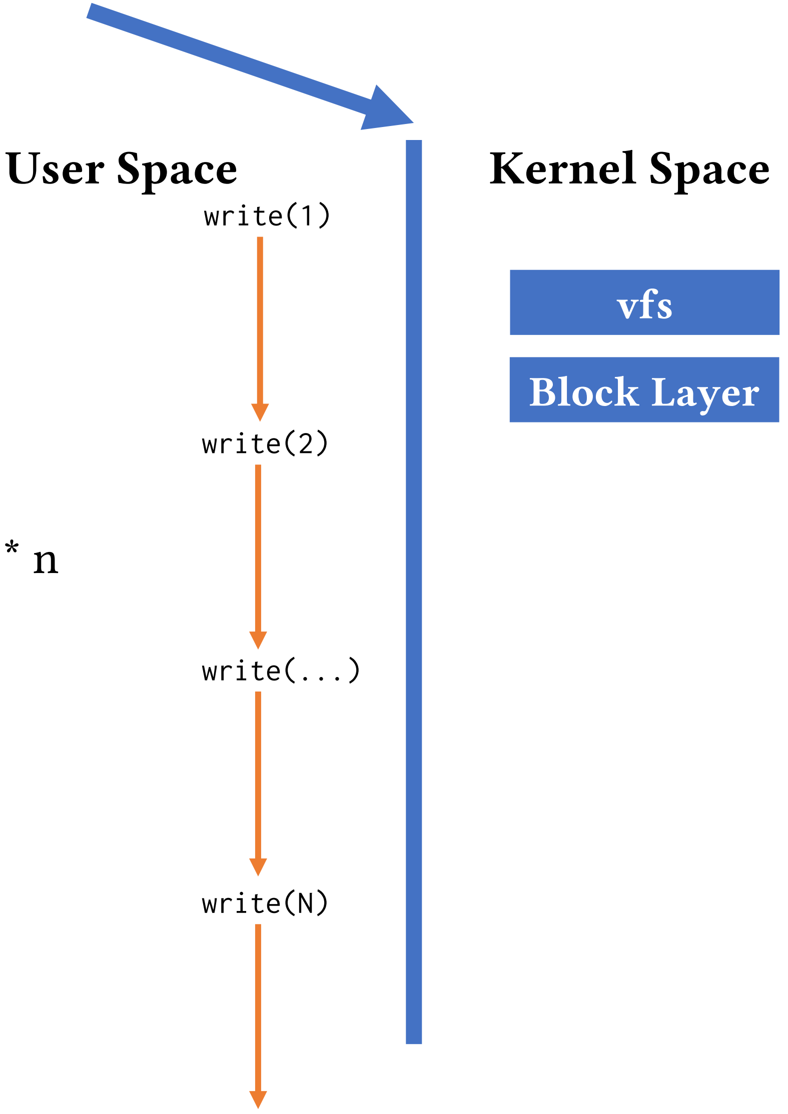


Time = orange * n



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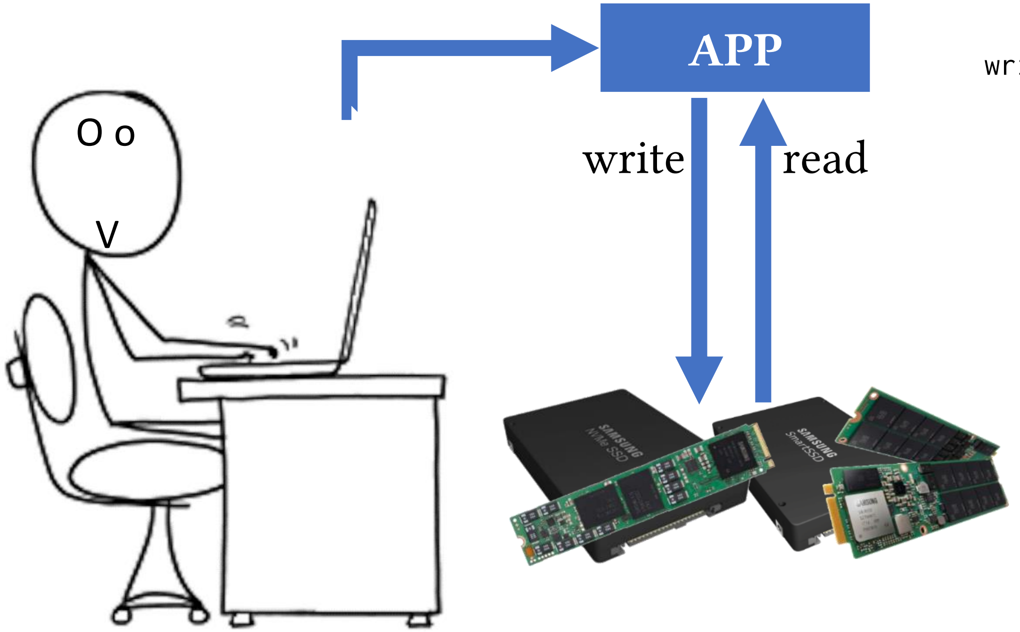

User Space

read()/write()
pread()/pwrite()
readv()/writev()
➔**Threadpool for scale**

`write(1)` `write(2)` `write(...)` `write(N)`

Time = orange + pool init

Kernel Space

vfs

Block Layer

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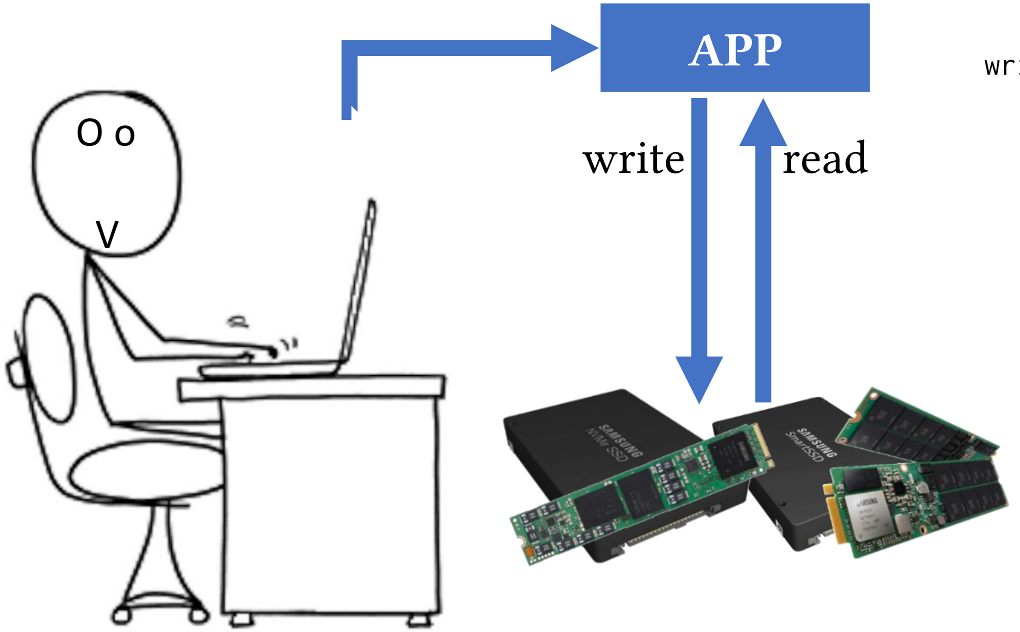

User Space

read()/write()
pread()/pwrite()
readv()/writev()
➔**Threadpool for scale**

`write(1)` `write(2)` `write(...)` `write(N)`

Applicable when
n < # cores
n < # cores you want to spent processing I/O

Kernel Space

vfs

Block Layer

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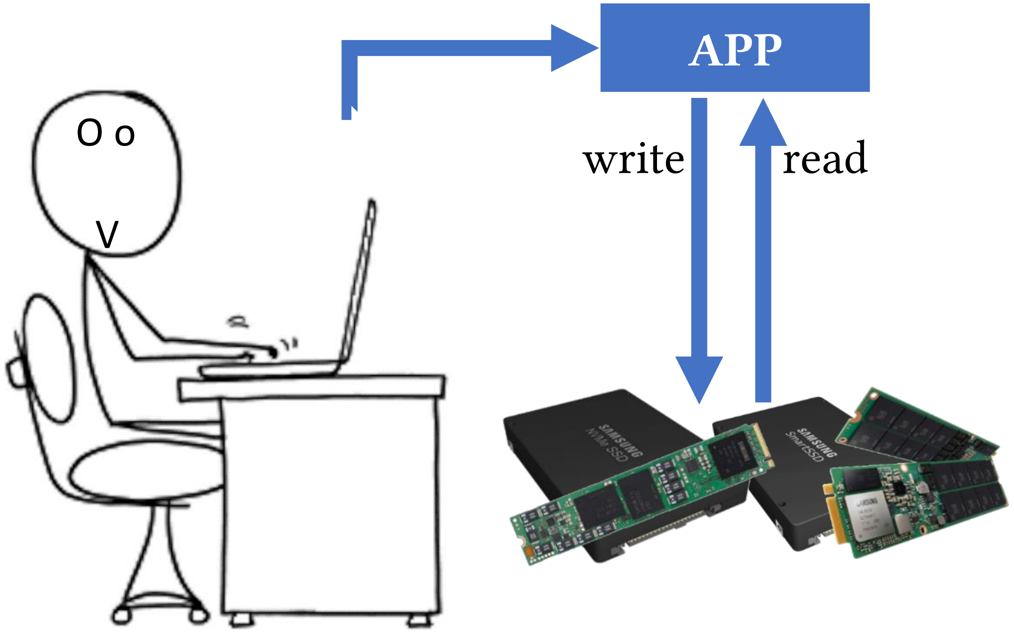

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Kernel Space

vfs

Block Layer

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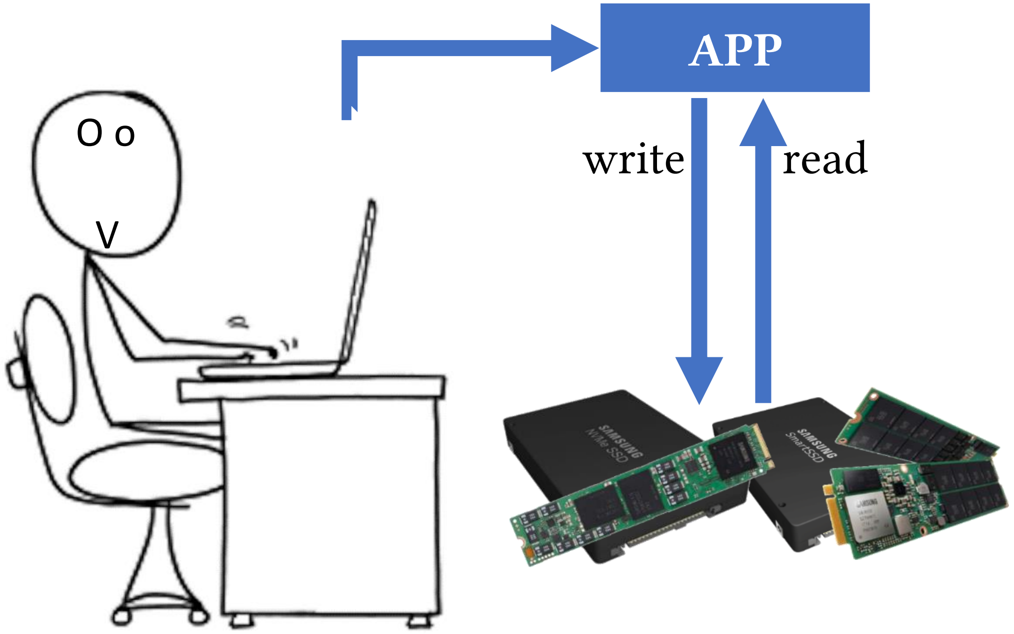

User Space | **Kernel Space**

read()/write()
pread()/pwrite()
readv()/writev()
➔Threadpool for scale
POSIX aio
Linux libaio
Windows IOCP
➔ Interrupt Driven

vfs
Block Layer
shared

```
write(1)
  write(2)
    write(...)
      write(N)
        cpl(1)
        cpl(2)
        cpl(…)
        cpl(N)
```

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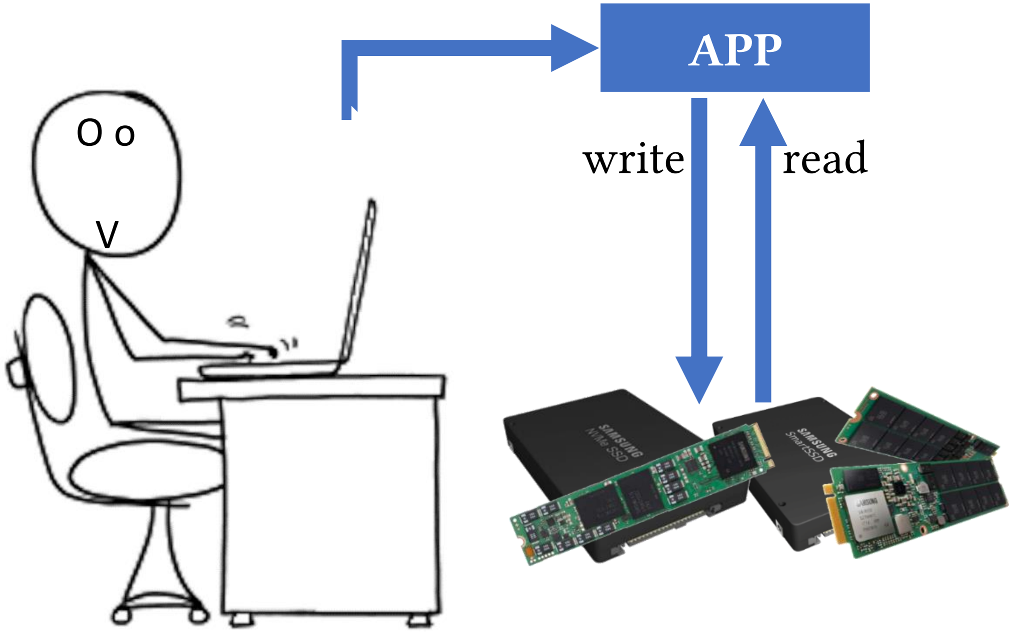

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io_uring

vfs
Block Layer
shared
shared

thread: sq poll
thread: driver-poll

```
write(1)
  write(2)
    write(...)
      write(N)
        cpl(1)
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        cpl(…)
        cpl(N)
```

Background

Reduce the cost of crossing the address-space boundary;
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Traditional + NVMe ZNS + KV

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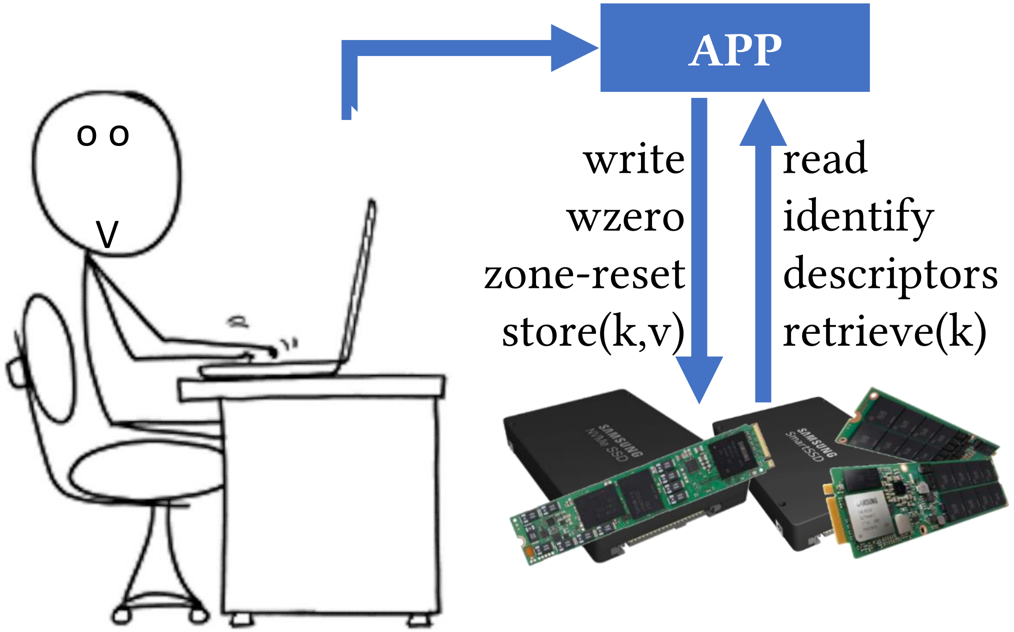

User Space | **Kernel Space**

read()/write()
pread()/pwrite()
readv()/writev()
➔Threadpool for scale
POSIX aio
Linux libaio
Windows IOCP
➔ Interrupt Driven
io_uring
ioctl() / devfs /sysfs

vfs
Block Layer
shared
shared
thread: sq poll
thread: driver-poll
NVMe

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APP

write
wzero
zone-reset
store(k,v)

read
identify
descriptors
retrieve(k)

User Space | **Kernel Space**

read()/write()
pread()/pwrite()
readv()/writev()
➔**Threadpool for scale**
POSIX aio
Linux libaio
Windows IOCP
➔ **Interrupt Driven**
io_uring

ioctl() / devfs /sysfs
SPDK/NVMe
(user space driver)
➔**Kernel Bypass**

vfs
Block Layer
shared
shared
thread: sq poll
thread: driver-poll
NVMe
vfio-pci /uio-generic

Background

I/O interface innovation

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- ~~I/O is just reading and writing~~
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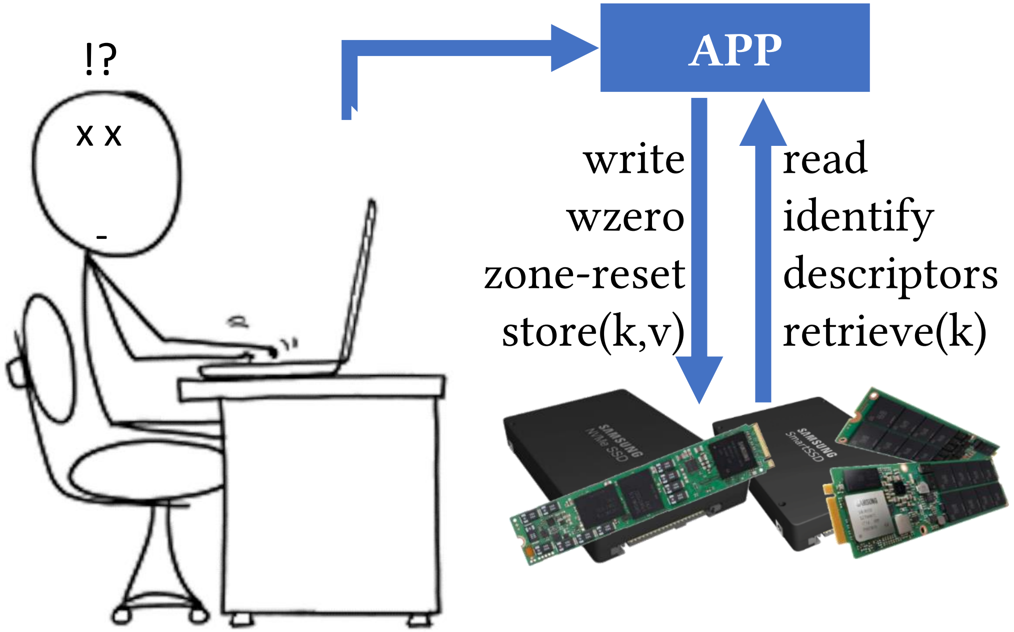

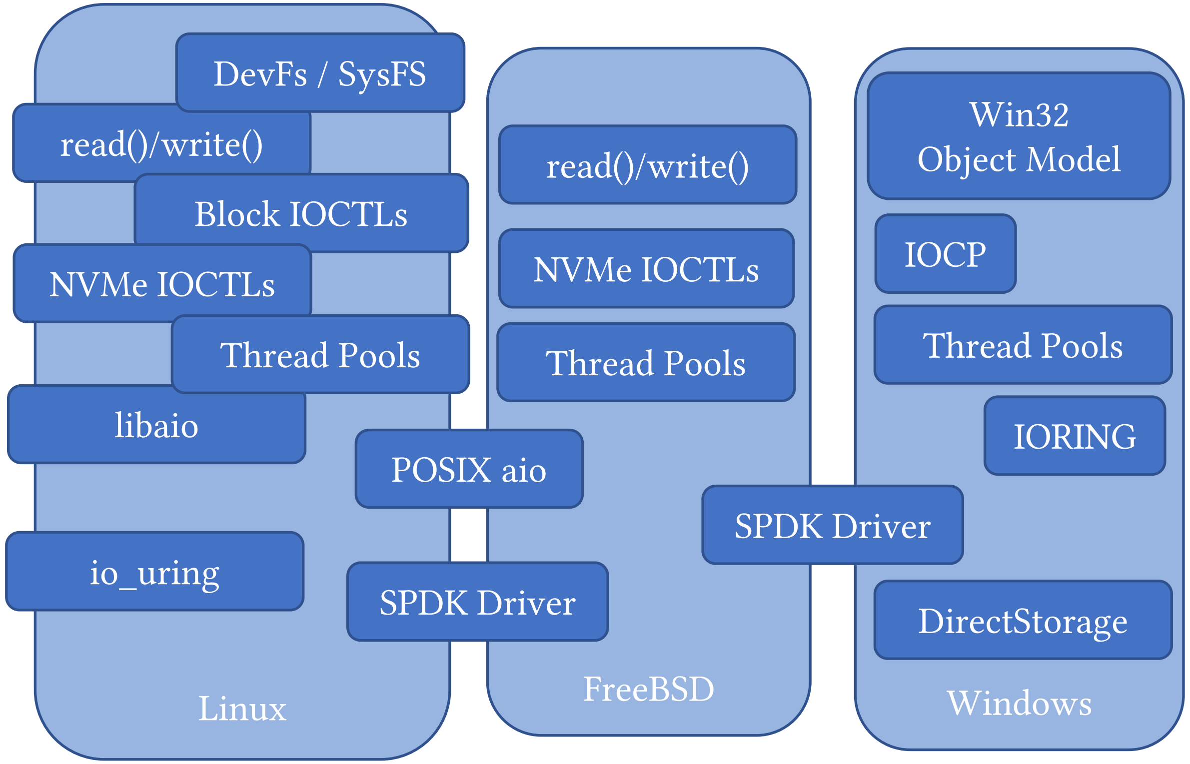

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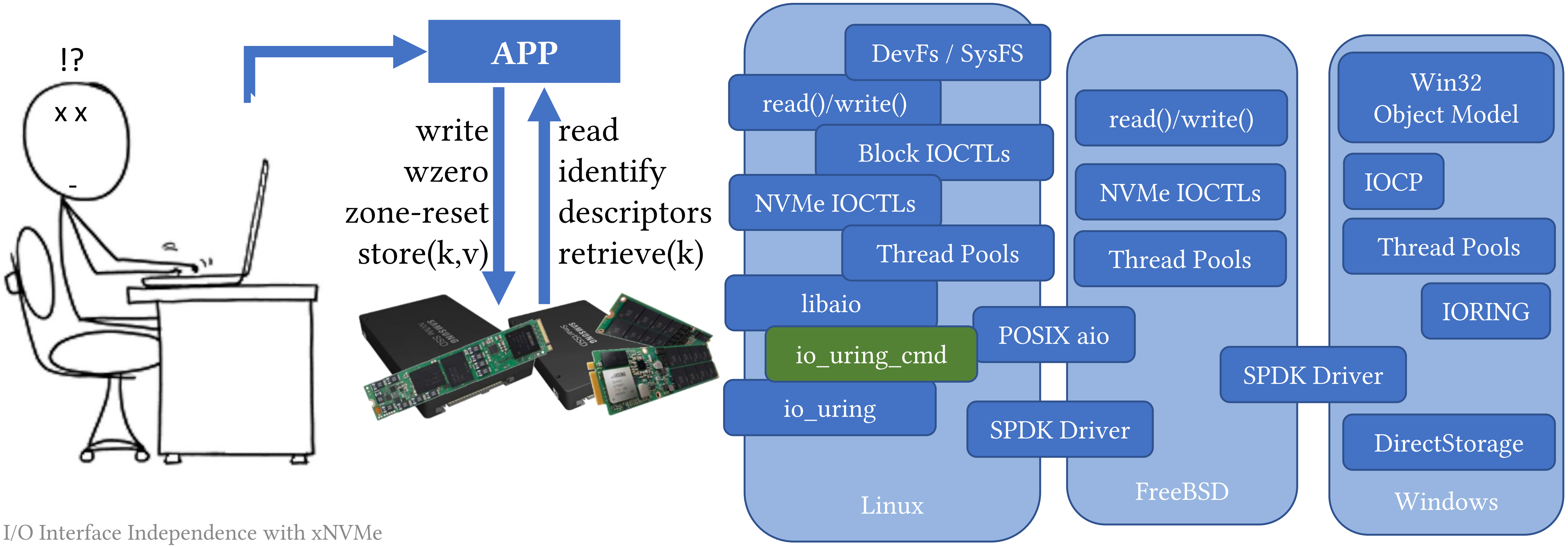

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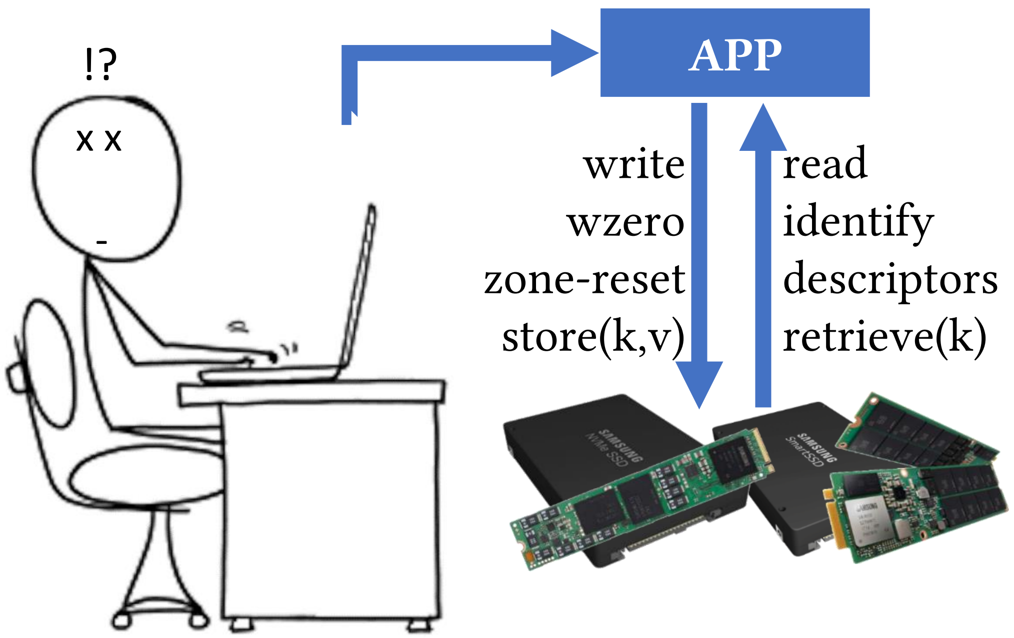
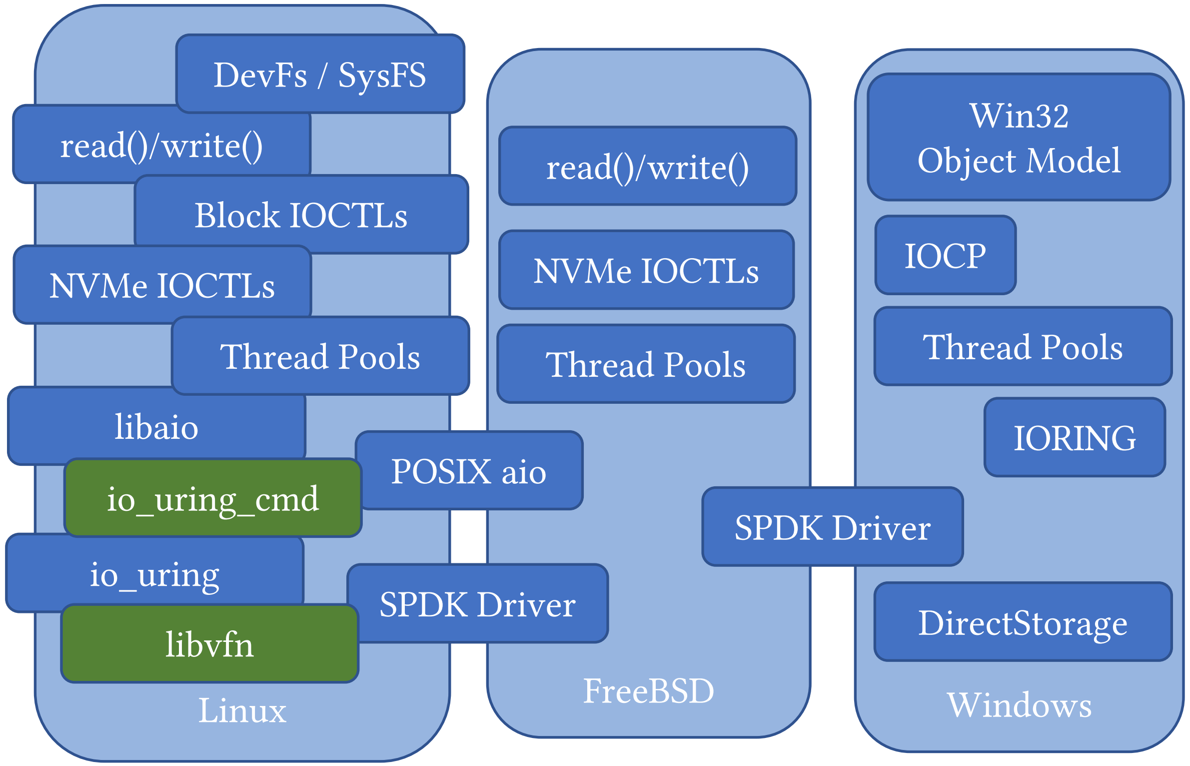
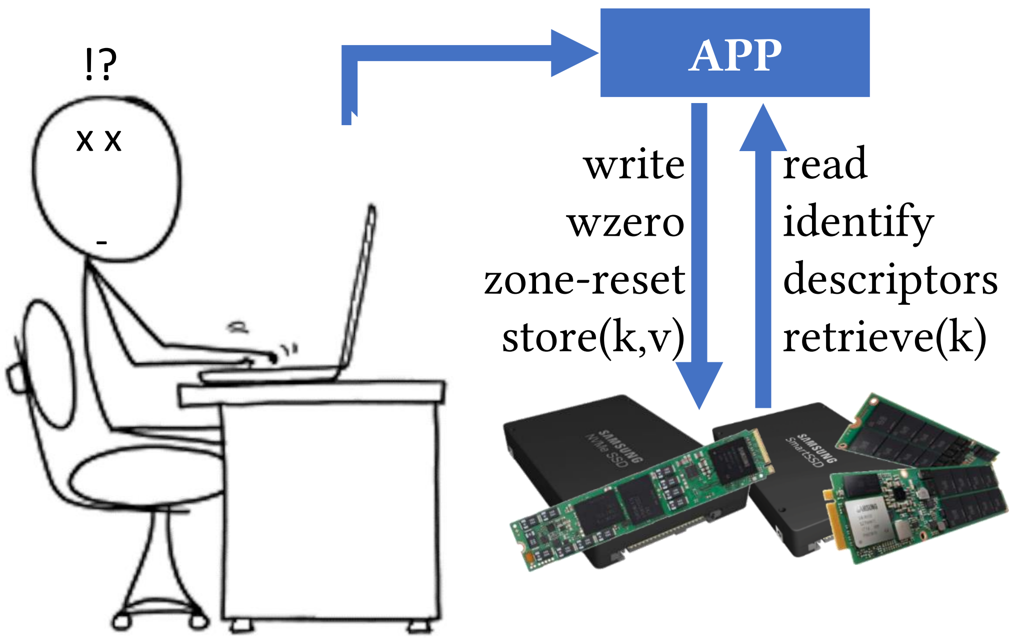
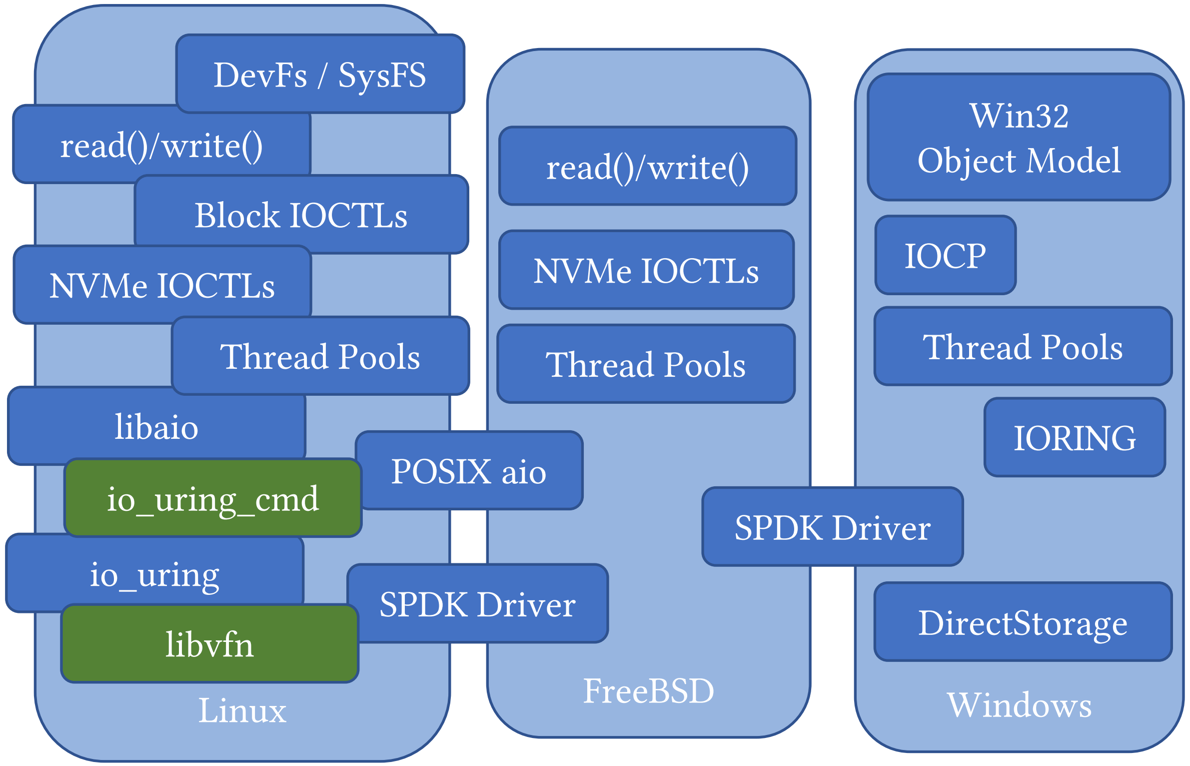




Background: the problem

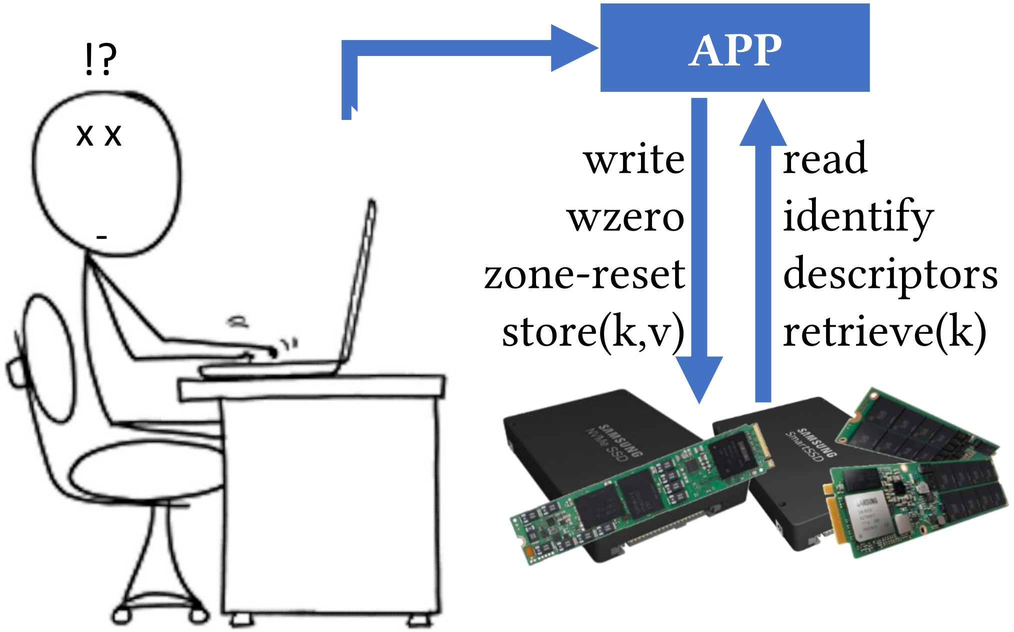
- We are in an interesting time of system interface changes, fluctuating from operating system managed, unikernels and OS bypass.
- Additionally, storage device interfaces are expanding with new command sets
- **Question:** How do you manage, and leverage, I/O interface innovation?

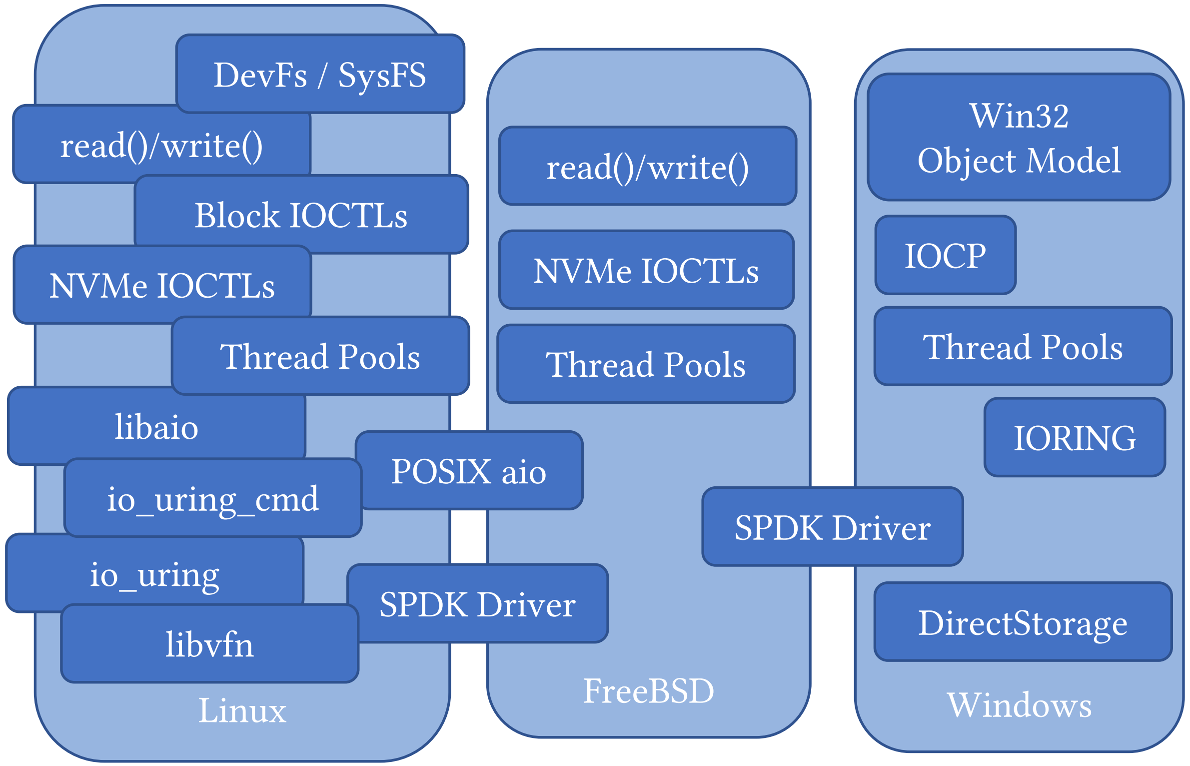




Background: the problem

- The wide span of system interfaces has become the **API**
- Thus, **applications** must implement them all or be **locked-in** to a single system
- **Question:** Is I/O interface independence possible?





Background: the problem

We denote **I/O interface independence** the following property of a data-intensive system: *changing I/O interface does not require refactoring the rest of the system.*

Our hypothesis is that I/O interface independence can be achieved at negligible performance cost.

Background: the problem

- **Negligible** performance cost, how much is that?

Background: the problem

- **Negligible** performance cost, how much is that?
- Ideally less than other means of I/O routing
  - I/O routing through PCIe switch ~**150 nsec**
  - I/O routing through PCH ~**865 nsec**
  - I/O routing through OS storage stack ~**1500 nsec**
- In relation to media access times
  - I/O access on ”fast” NAND in an NVMe SSD ~**7.000 nsec**
  - I/O access on ”slow” NAND in an NVMe SSD is ~**60.000 nsec**

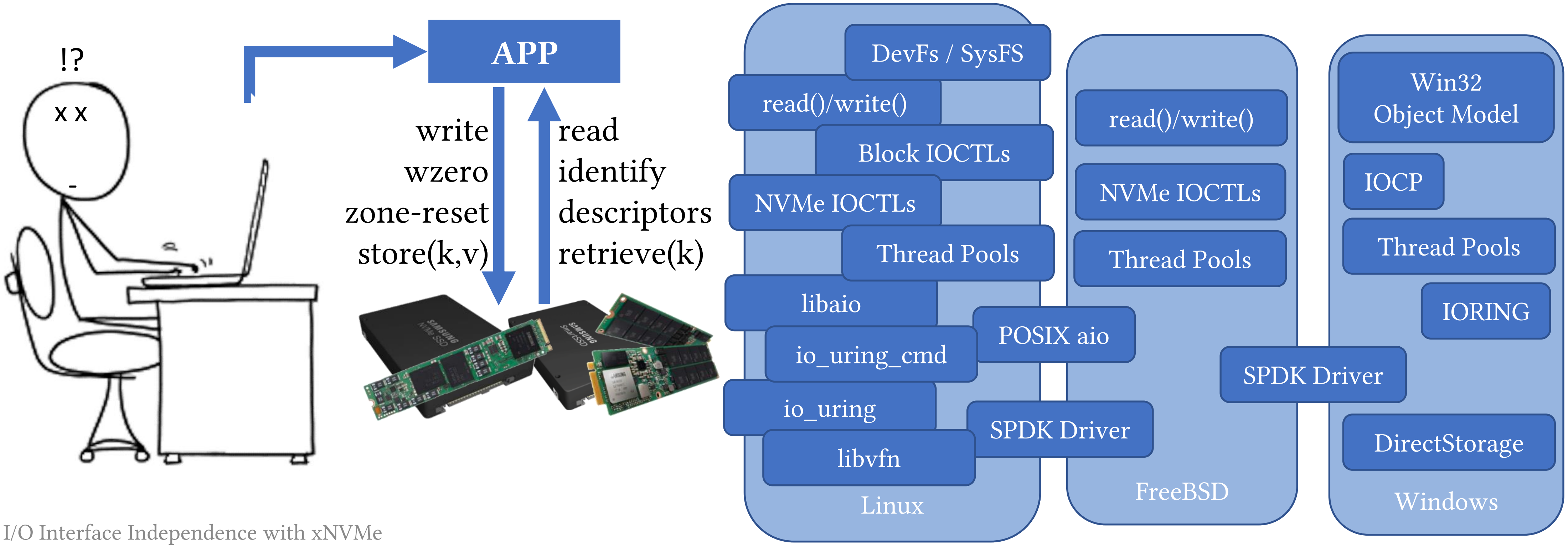
- **Negligible**, a small fraction of media-access time, relative to other means of I/O routing ➔ low hundreds

4k random read at QD1	Latency (**nsec**)
Connected via **PCIe slot** **Lanes directly to CPU**	6455

4k random read at QD1	Latency (**nsec**)
Connected via **M.2** port **Lanes via PCH to CPU**	7376

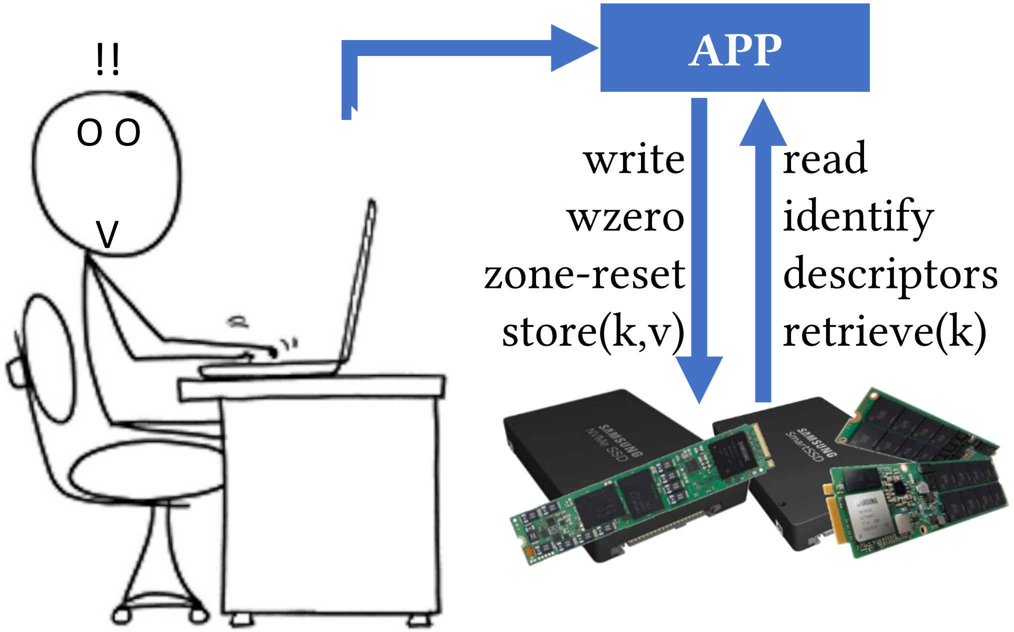
Background: the problem

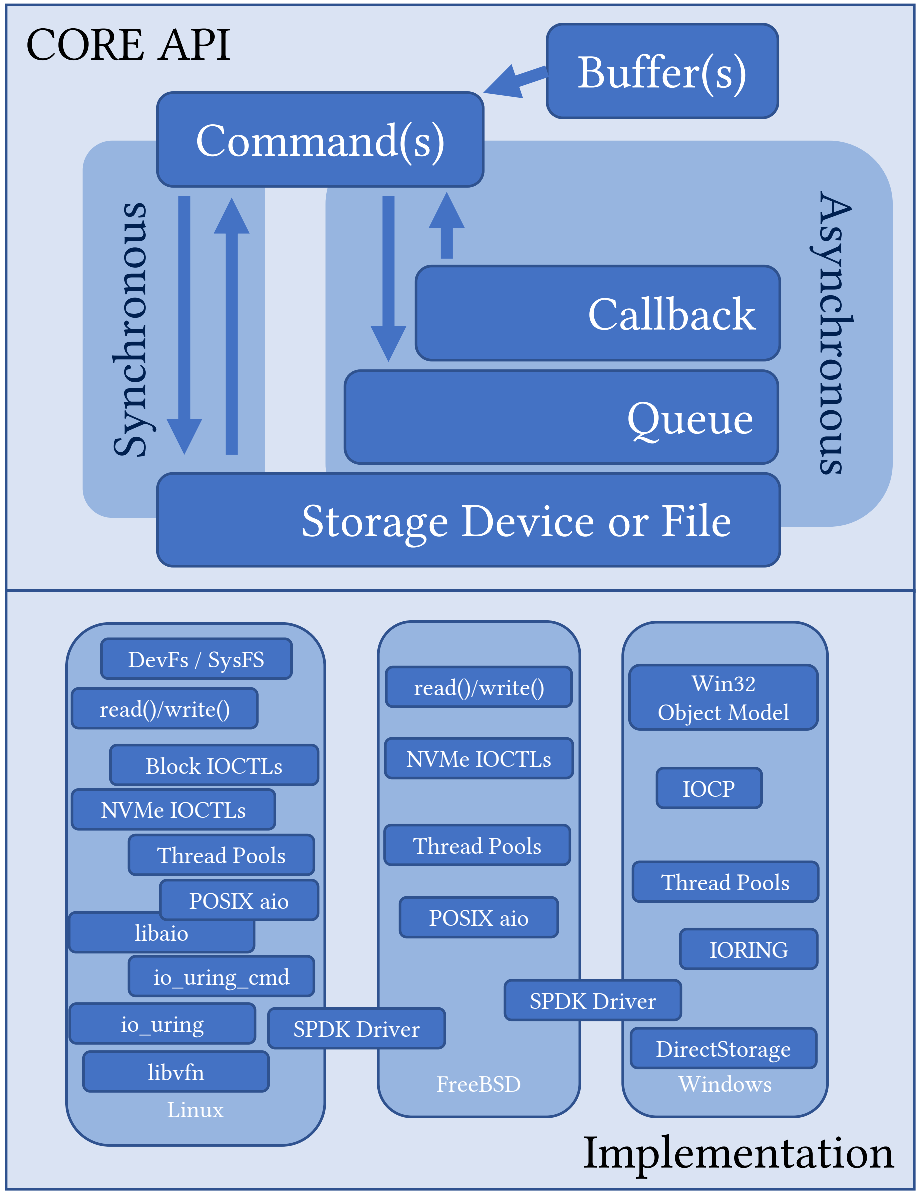
- **Questions**
  - Is I/O interface independence possible? And at what cost?
  - How do you manage, and leverage, I/O interface innovation?



I/O Interface Independence with **xNVMe**

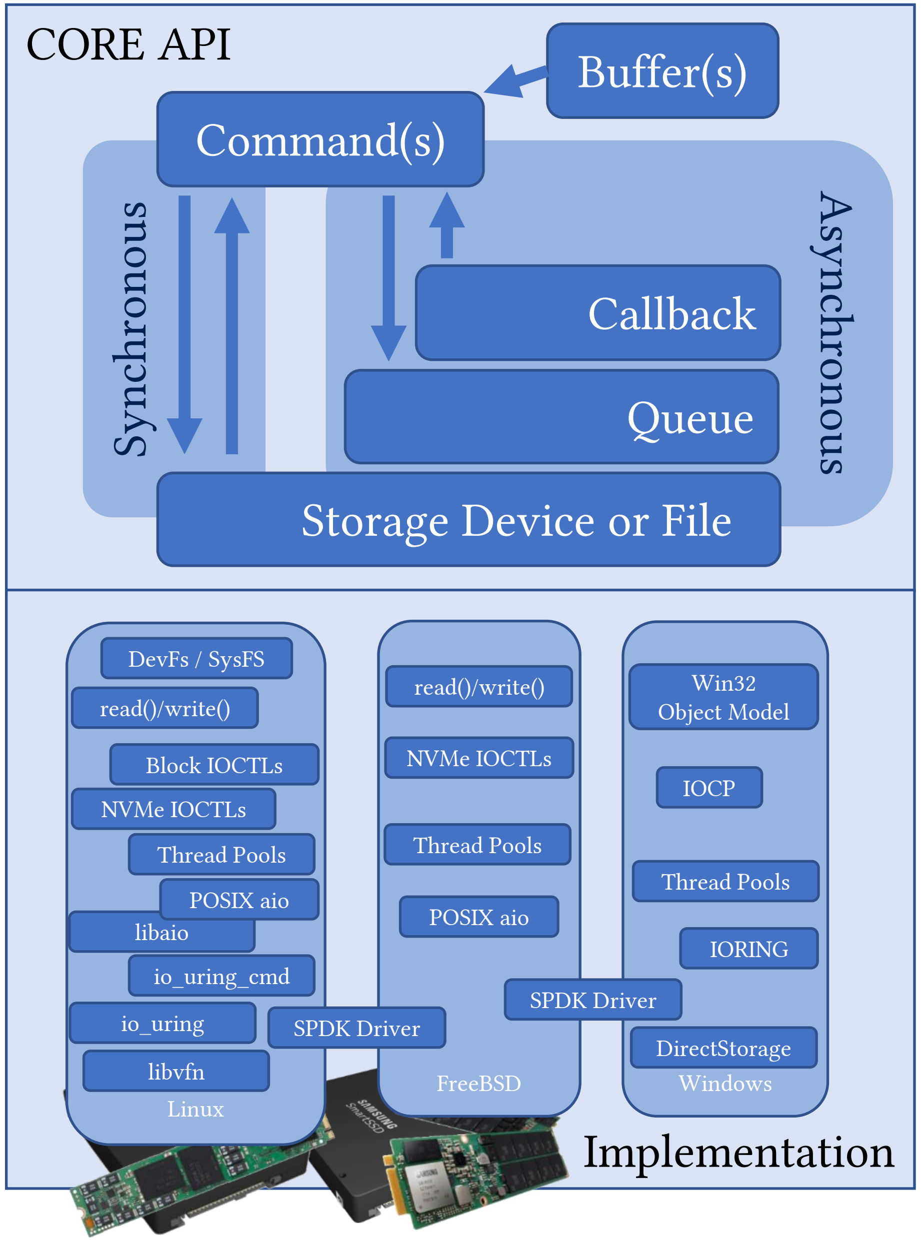
- I/O interface independence with negligible performance cost
  - Extensible, Simple and Uniform
- Minimal spanning-layer





I/O Interface Independence with **xNVMe**: API

- Device Handles
- Buffers
- Commands
  - Synchronous
  - Asynchronous



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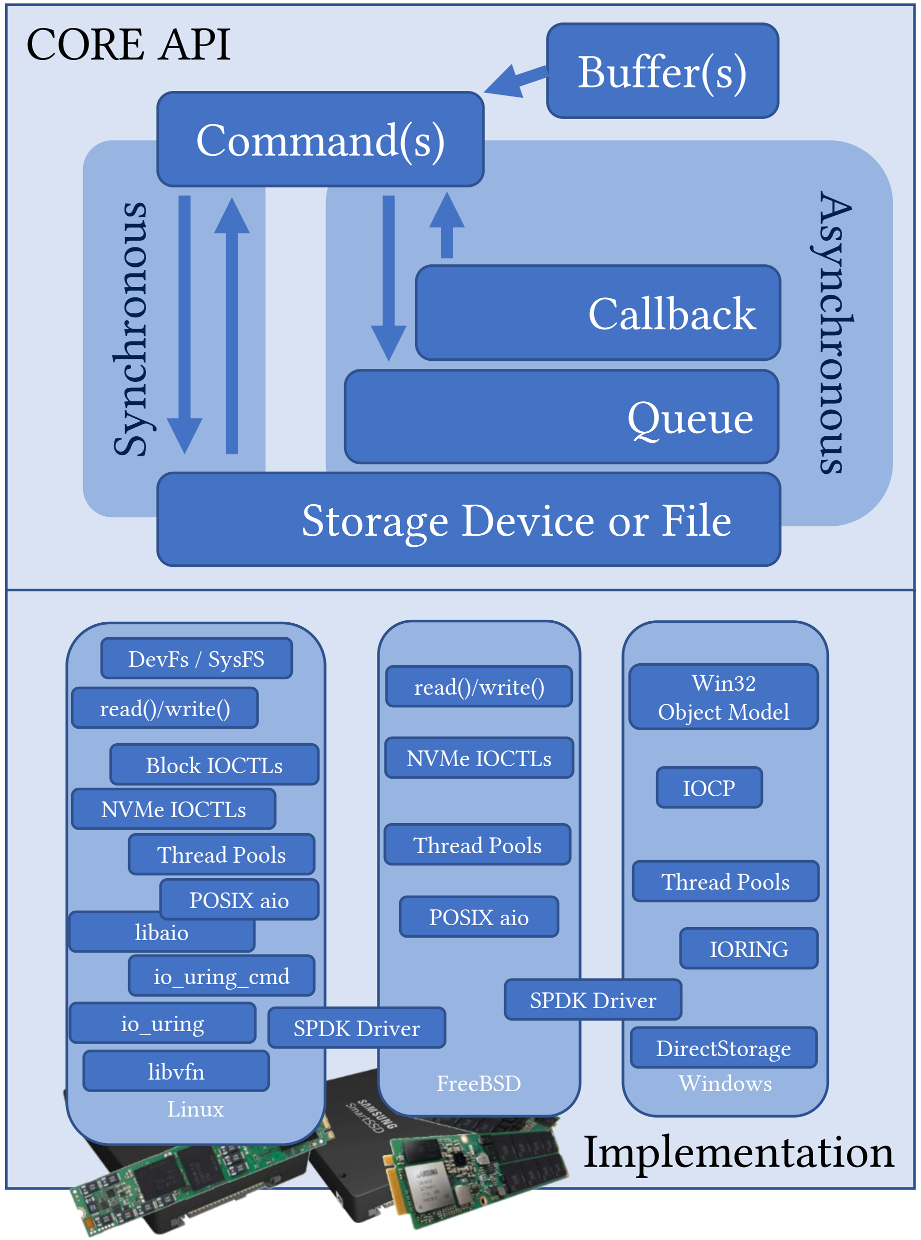

I/O Interface Independence with **xNVMe:** API

- **Device Handles**
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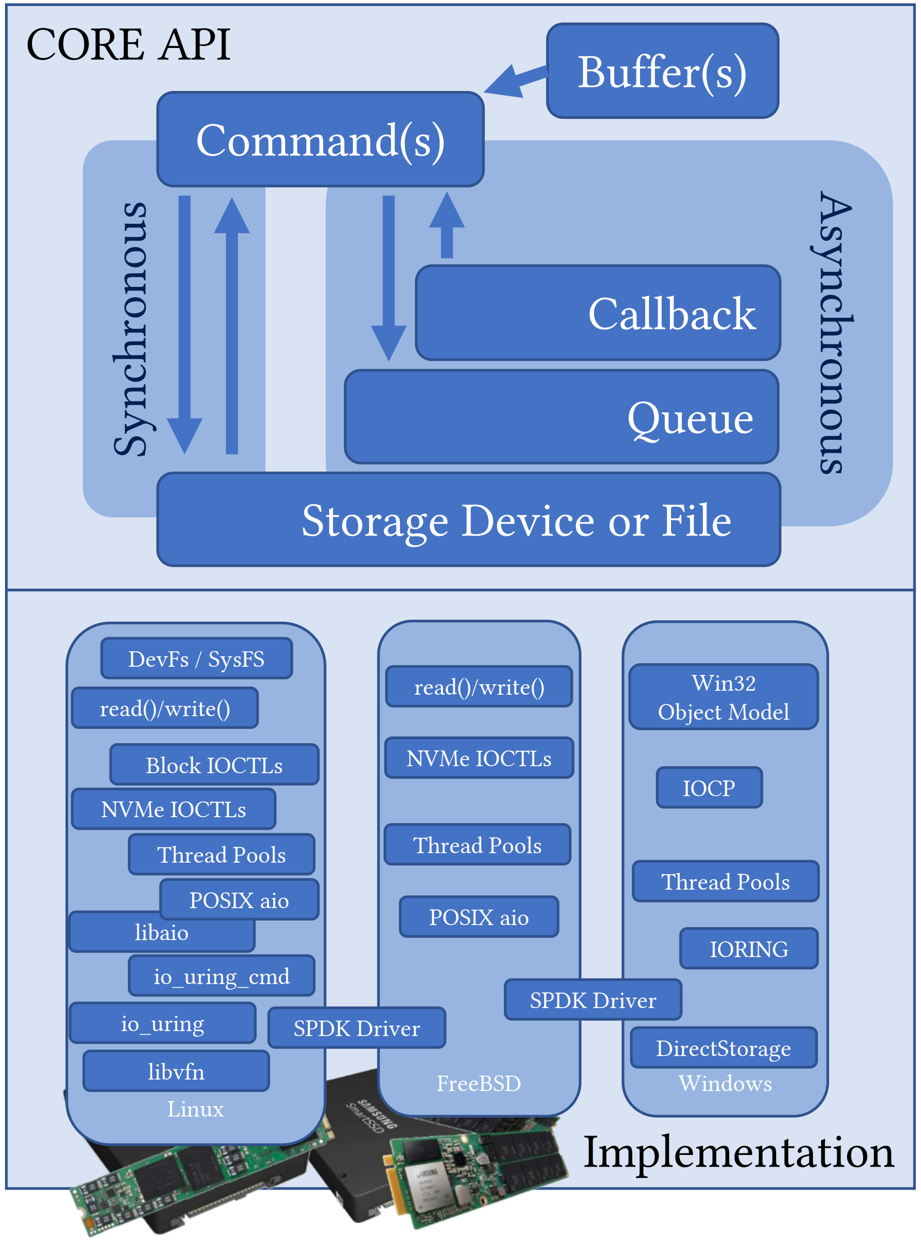
  - `xnvme_dev_open(uri, opts)`



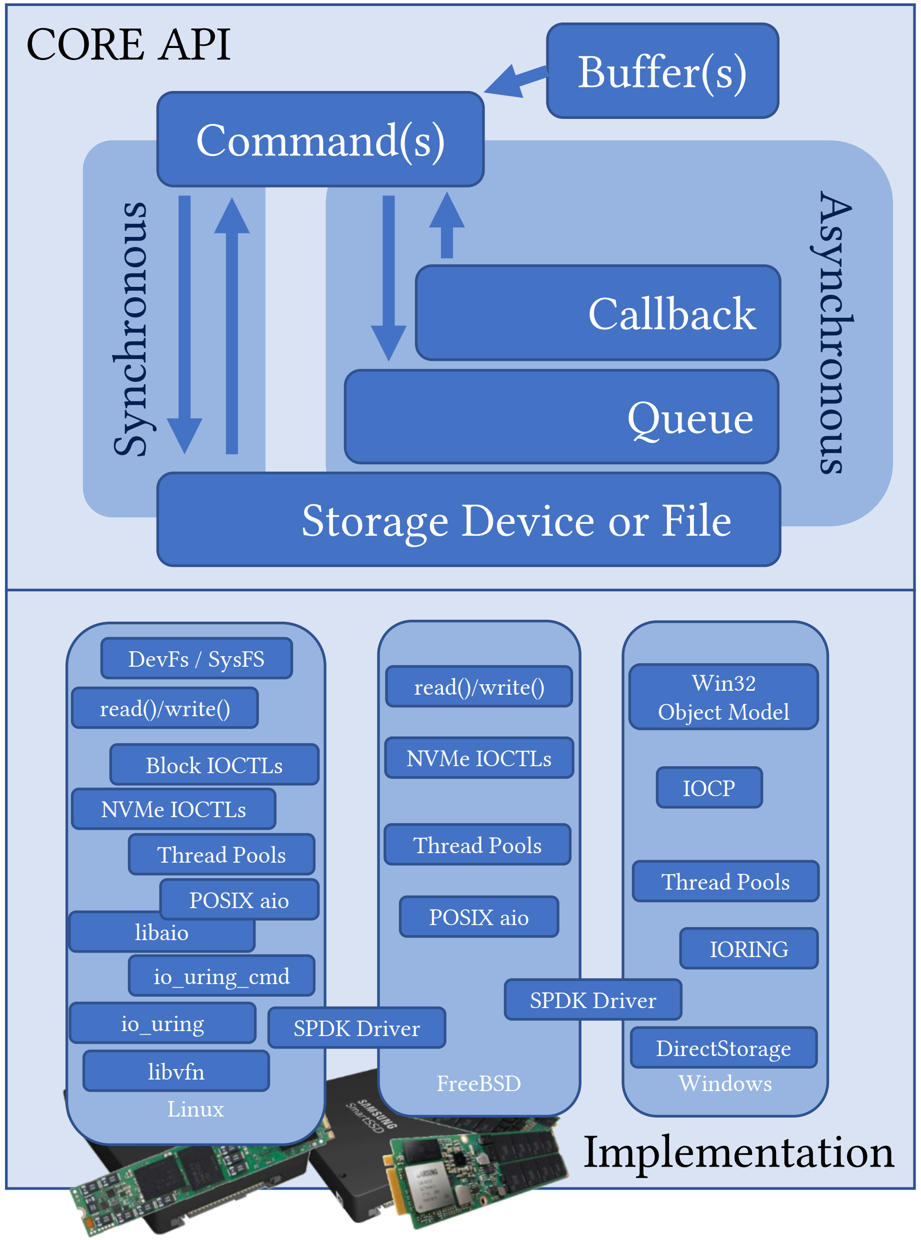
I/O Interface Independence with **xNVMe**: API

Invoked for each device
cb(dev, args)

- **Device Handles**
  - xnvme_enumerate(uri, opts, cb, args)

NULL
Local system

“10.11.12.185:4420”
Fabrics Transport



I/O Interface Independence with **xNVMe**: API

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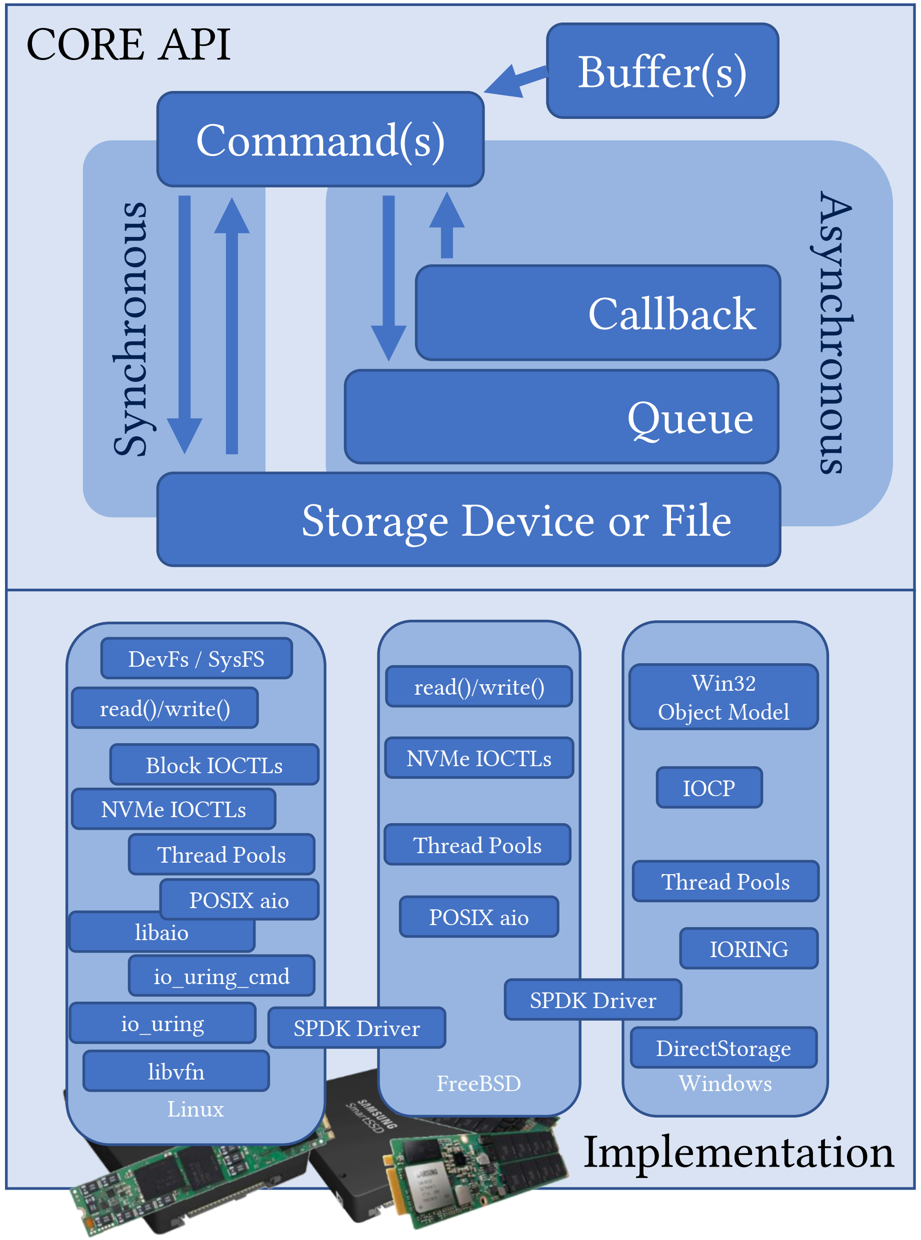
NULL
Local system

User space NVMe Driver

```
root@corei5:~# xnvme enum
xnvme_enumeration:
  - {uri: '0000:04:00.0', dtype: 0x2, nsid: 0x1, csi: 0x0}
  - {uri: '/dev/nvme0n1', dtype: 0x2, nsid: 0x1, csi: 0x0}
  - {uri: '/dev/ng0n1', dtype: 0x2, nsid: 0x1, csi: 0x0}
```

OS Managed NVMe NS (Block Device)

OS Managed NVMe NS (Char Device)



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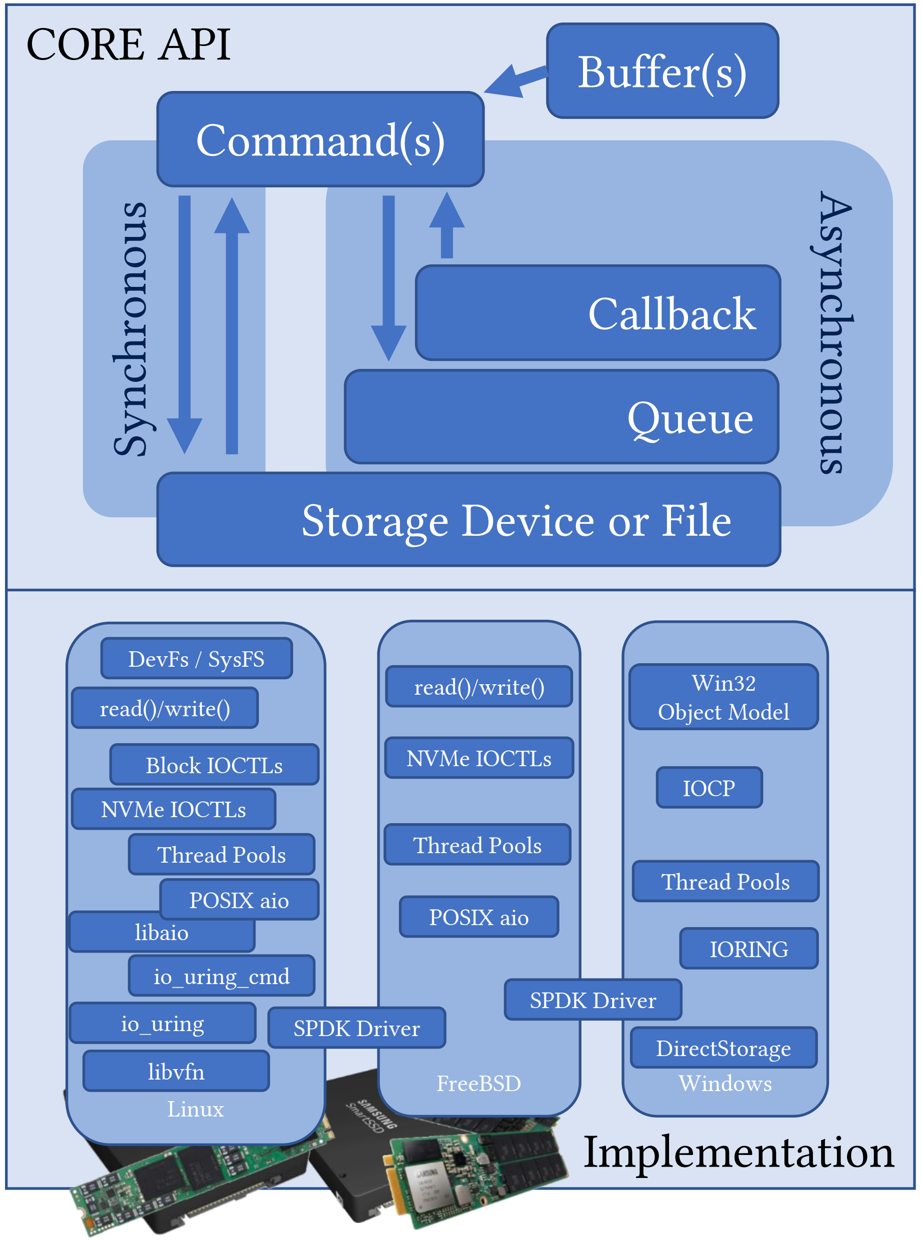
“10.11.12.185:4420”
Fabrics Transport

```
safl@debtop:~$ xnvme enum --uri 10.11.12.185:4420
xnvme_enumeration:
  - {uri: '10.11.12.185:4420', dtype: 0x2, nsid: 0x1, csi: 0x0}
safl@debtop:~$ 
```



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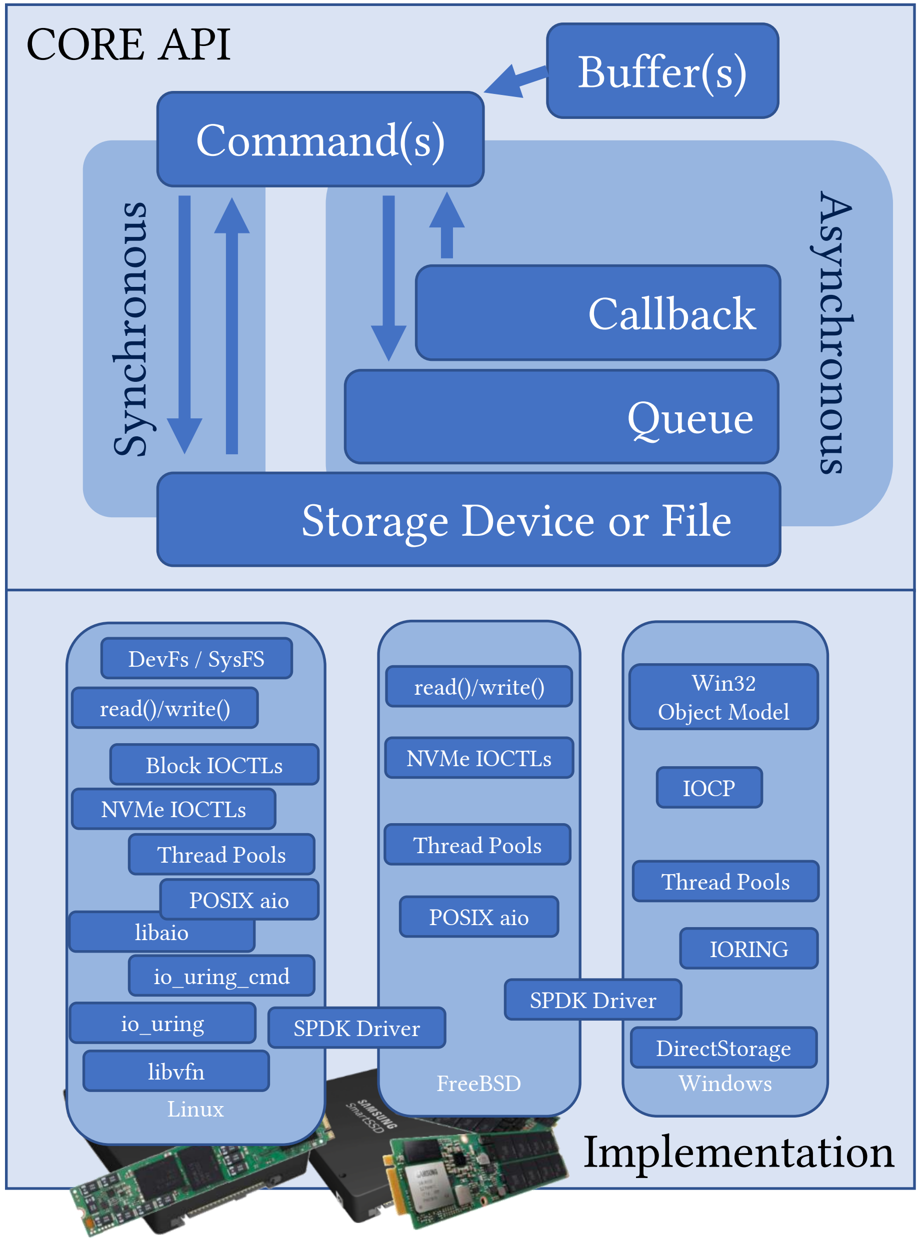

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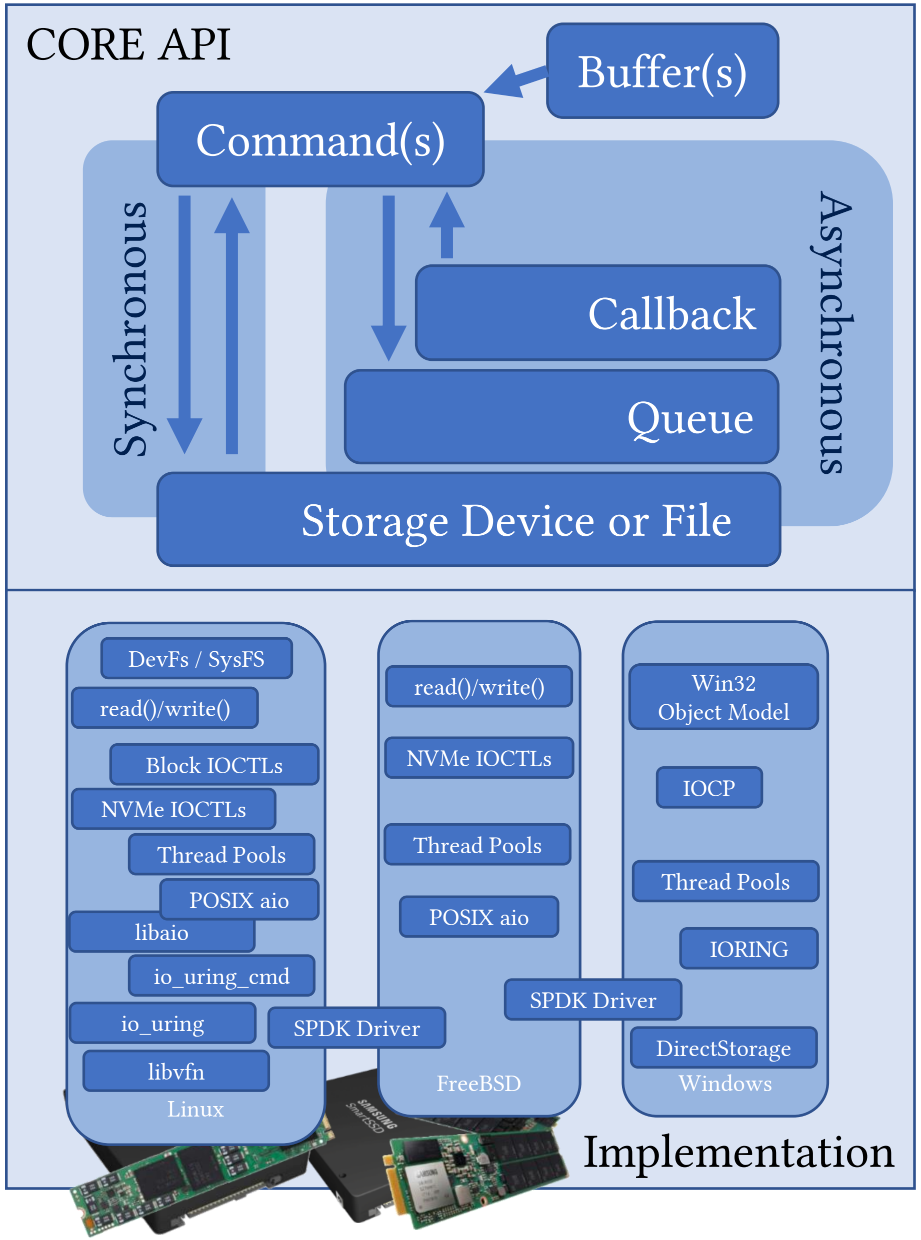

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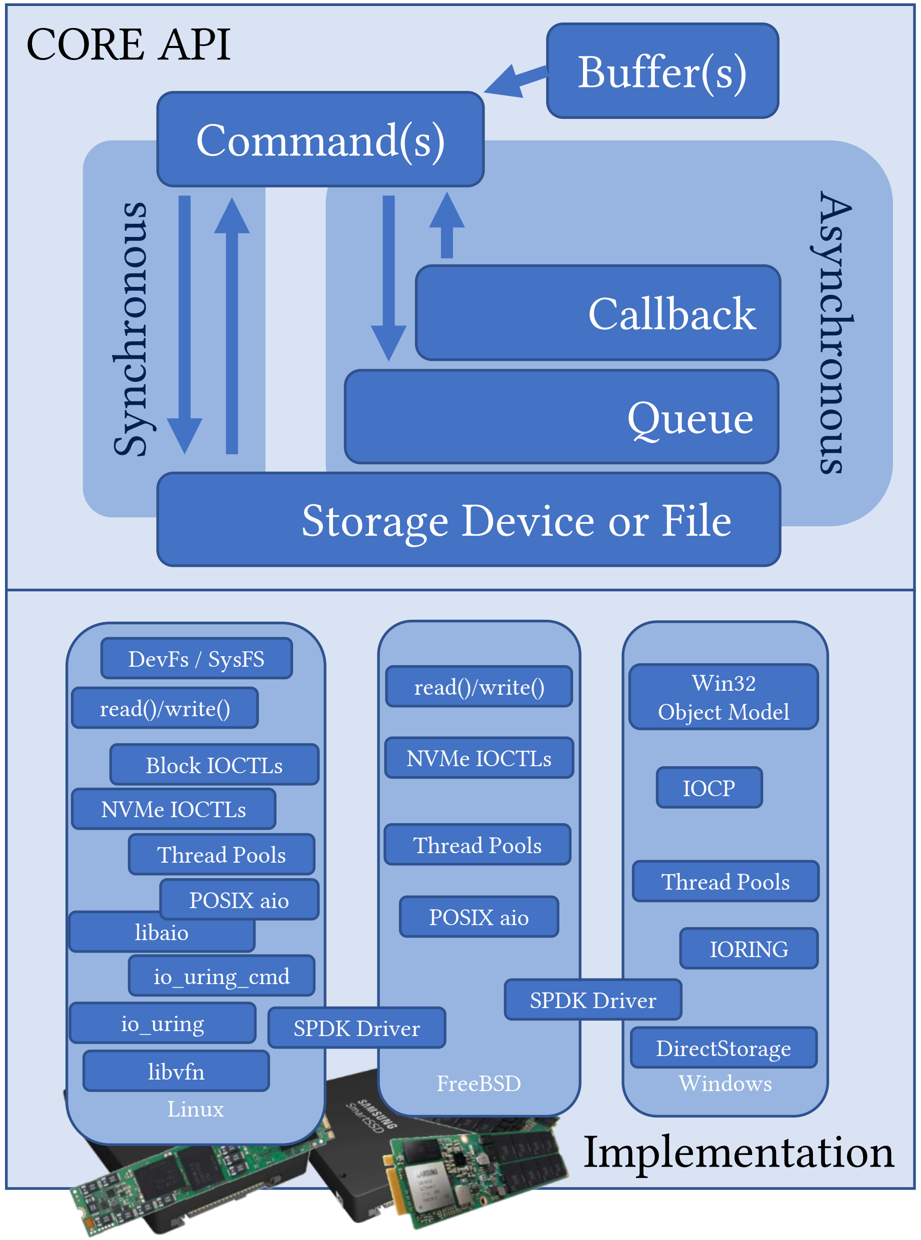
```
xnvme info /dev/ng0n1 --dev-nsid 0x1
xnvme info 0000:04:00.0 --dev-nsid 0x1
xnvme info 10.11.12.185:4420 -dev-nsid 0x1
xnvme info /dev/sda
xnvme info /dev/nullb0
```



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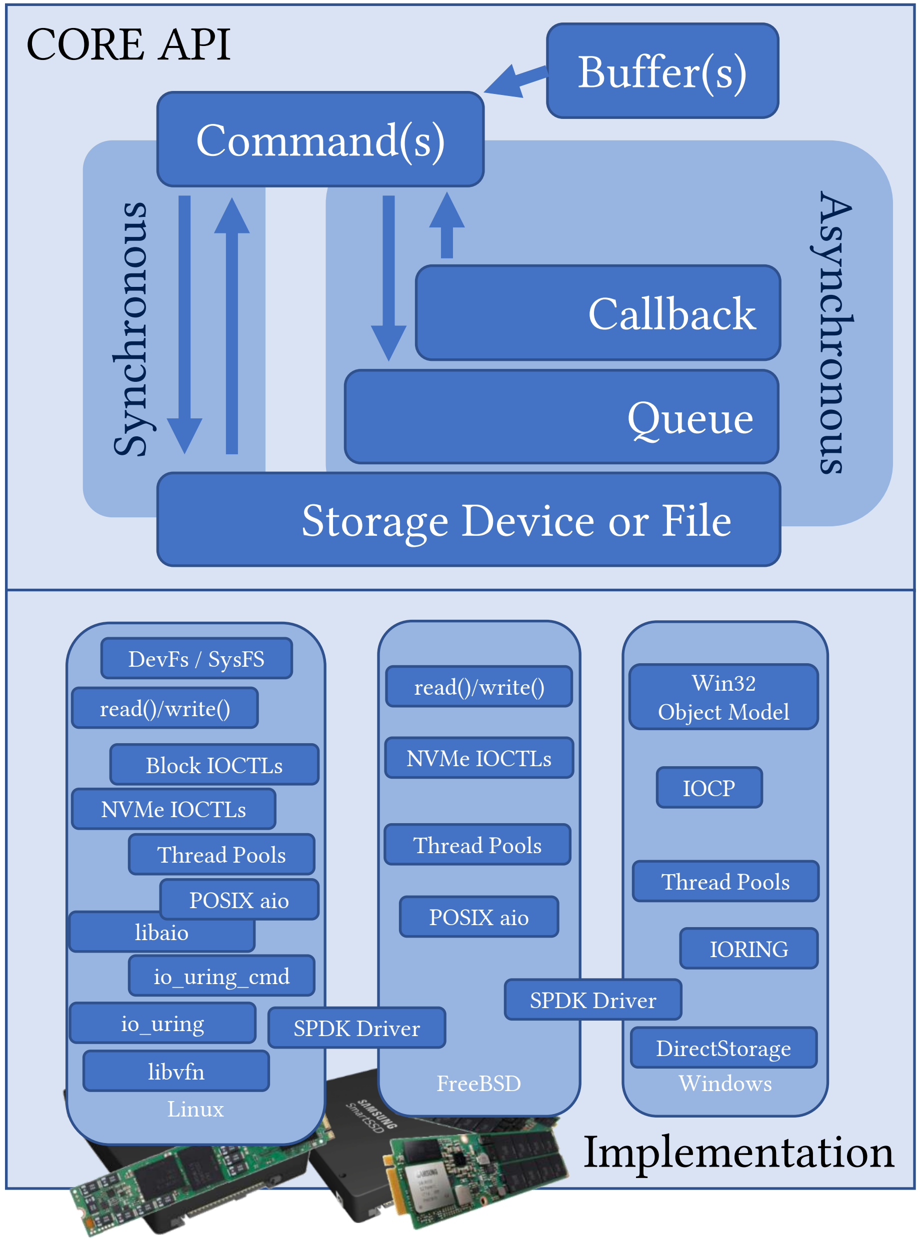
xnvme info 10.11.12.185:4420 -dev-nsid 0x1
```

Traditional {
```
xnvme info /dev/sda
xnvme info /dev/nullb0
```



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- **Device Handles**
  - `xnvme_enumerate(uri, opts, cb, args)`
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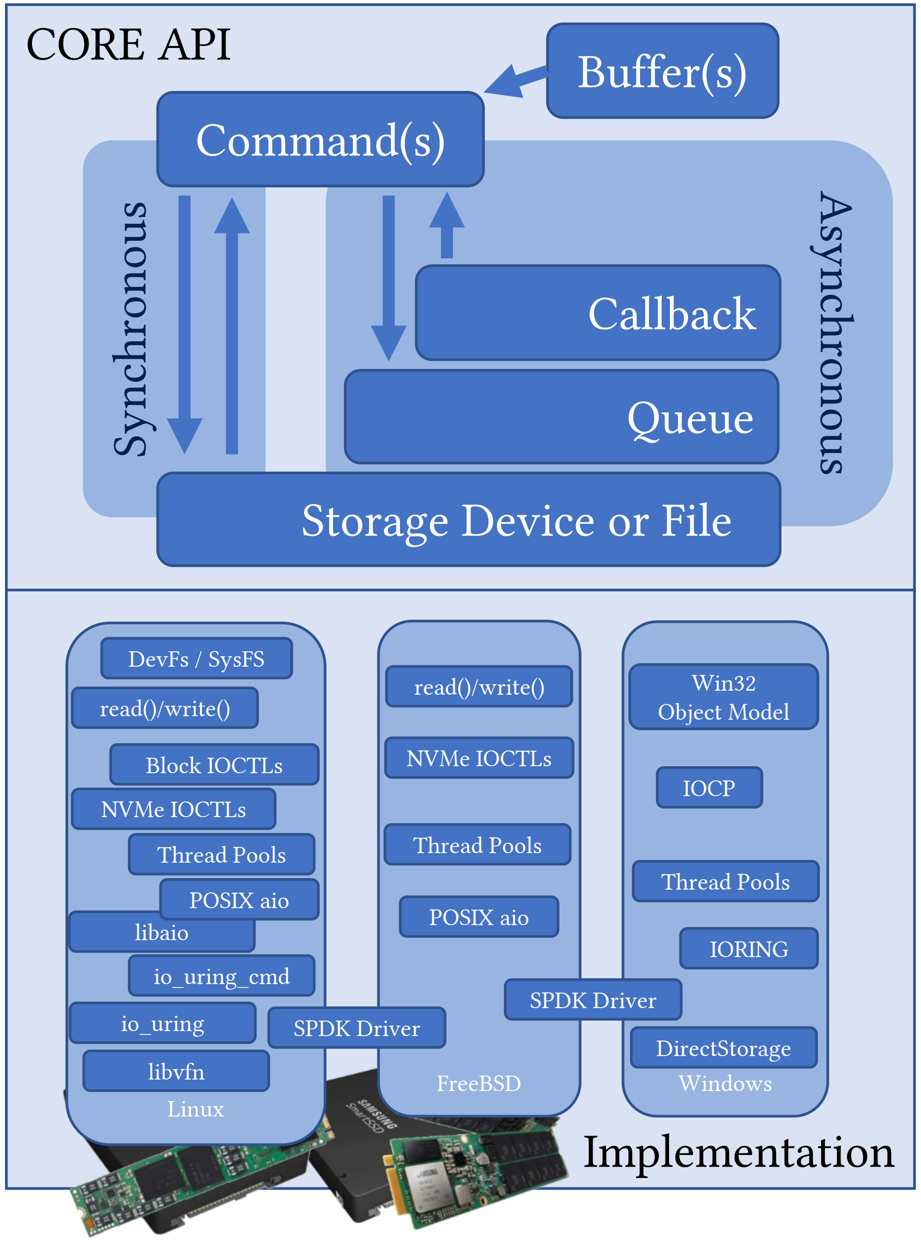
NVMe {
```
xnvme info /dev/ng0n1 --dev-nsid 0x1
xnvme info 0000:04:00.0 --dev-nsid 0x1
xnvme info 10.11.12.185:4420 -dev-nsid 0x1
```

Traditional {
```
xnvme info /dev/sda
xnvme info /dev/nullb0
```



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NVMe:
```
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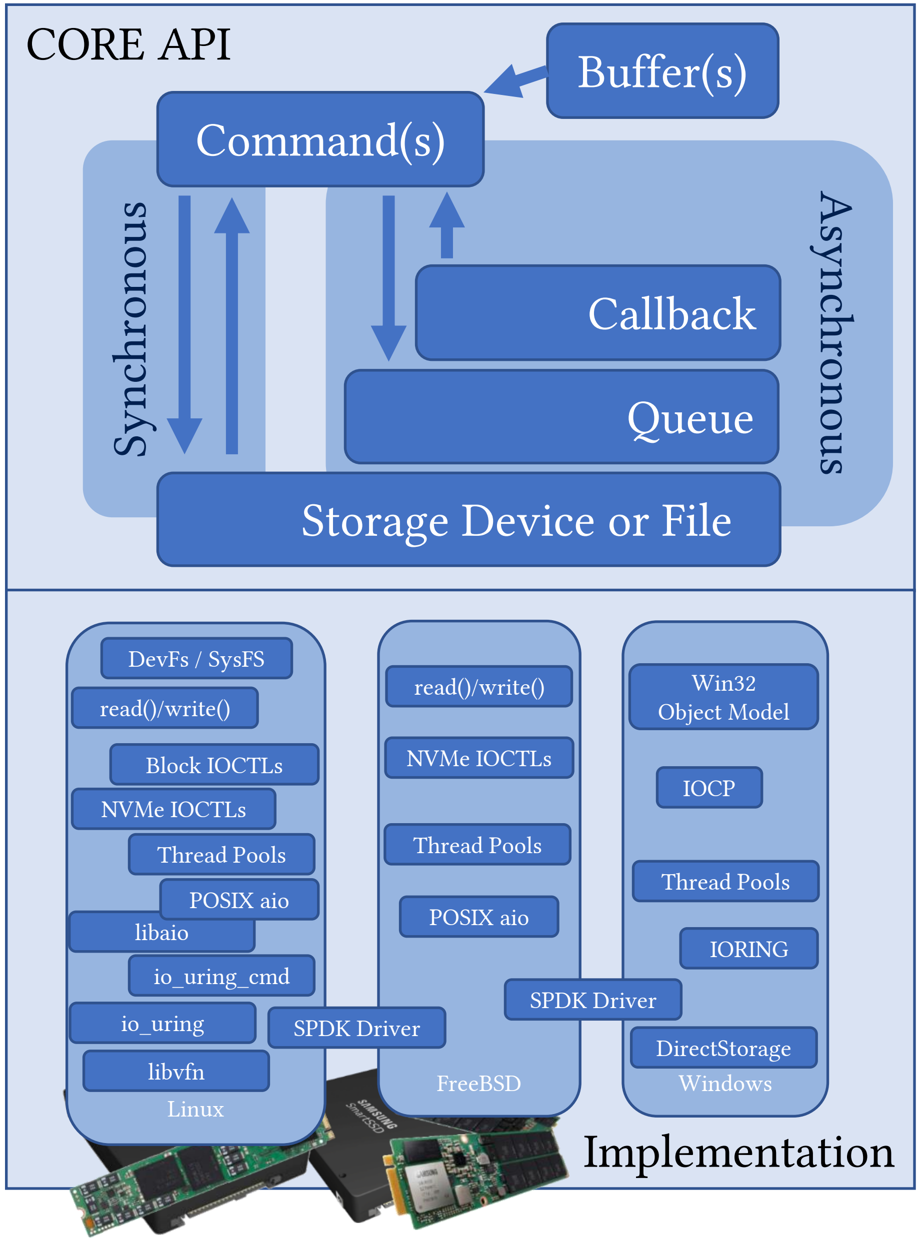
xnvme info 10.11.12.185:4420 -dev-nsid 0x1
```

Traditional:
```
xnvme info /dev/sda
xnvme info /dev/nullb0
```

  - OPTS Examples (C API)

```
opts = { .async = "io_uring" }
opts = { .async = "libaio" }
opts = { .async = "thrpool", .sync = "nvme" }
opts = { .async = "thrpool", .sync = "psync" }
```



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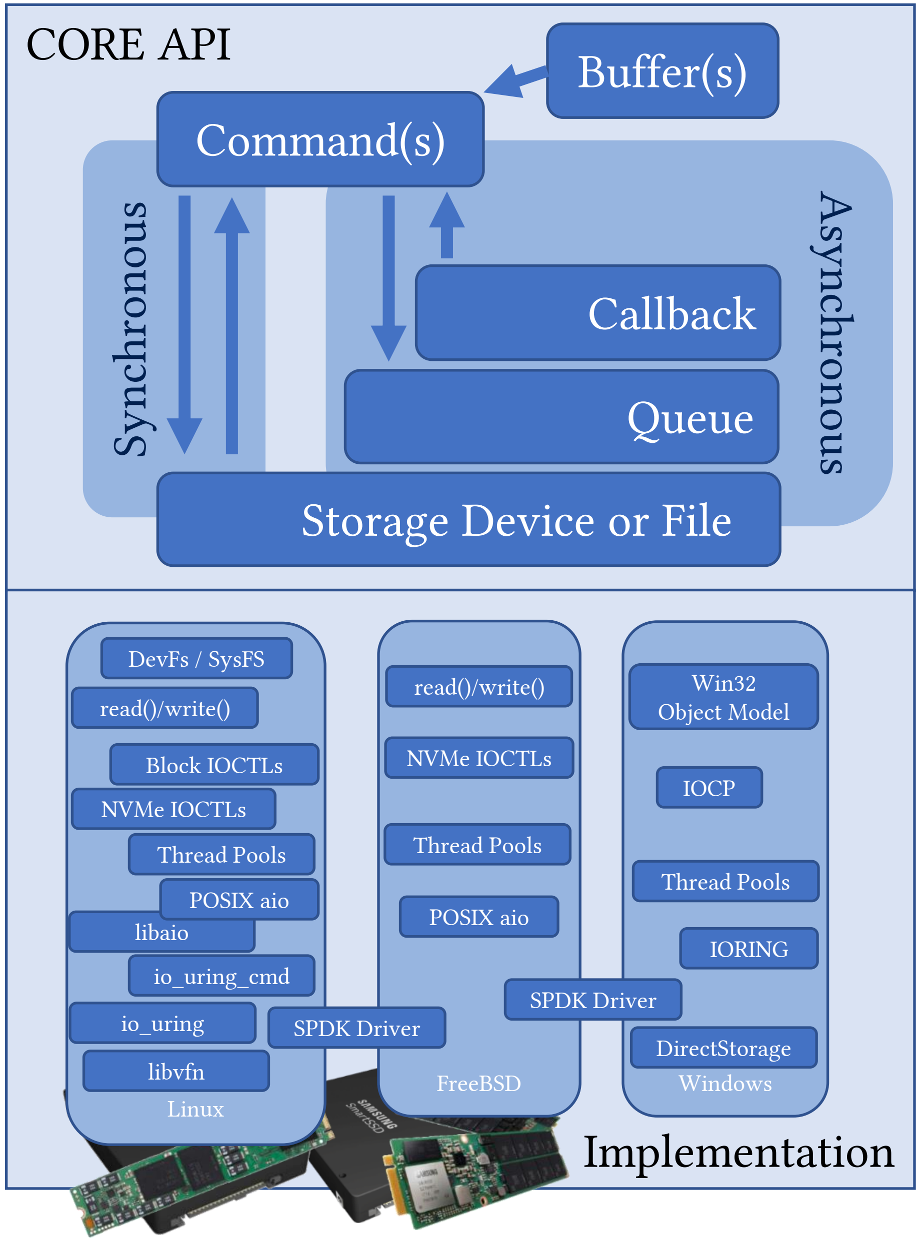

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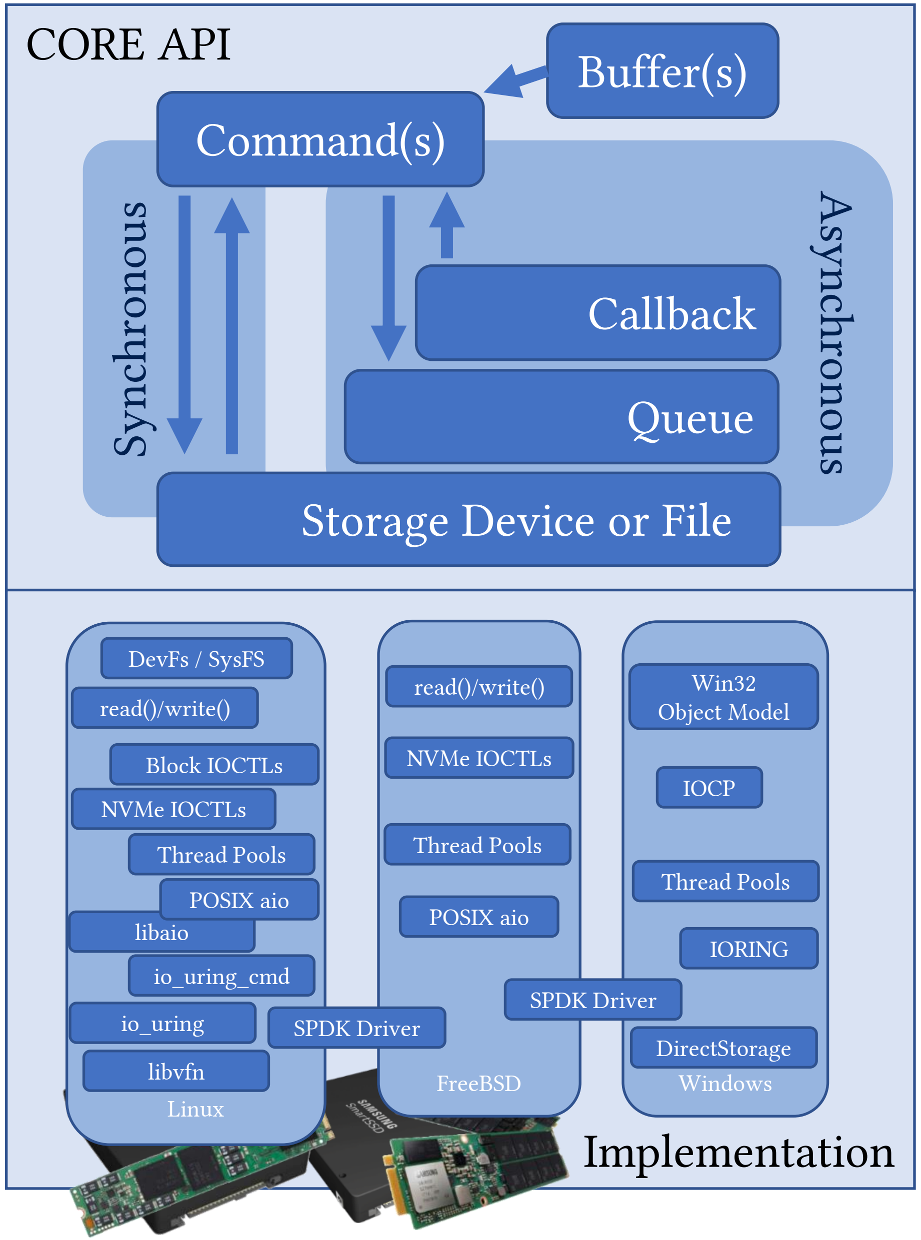
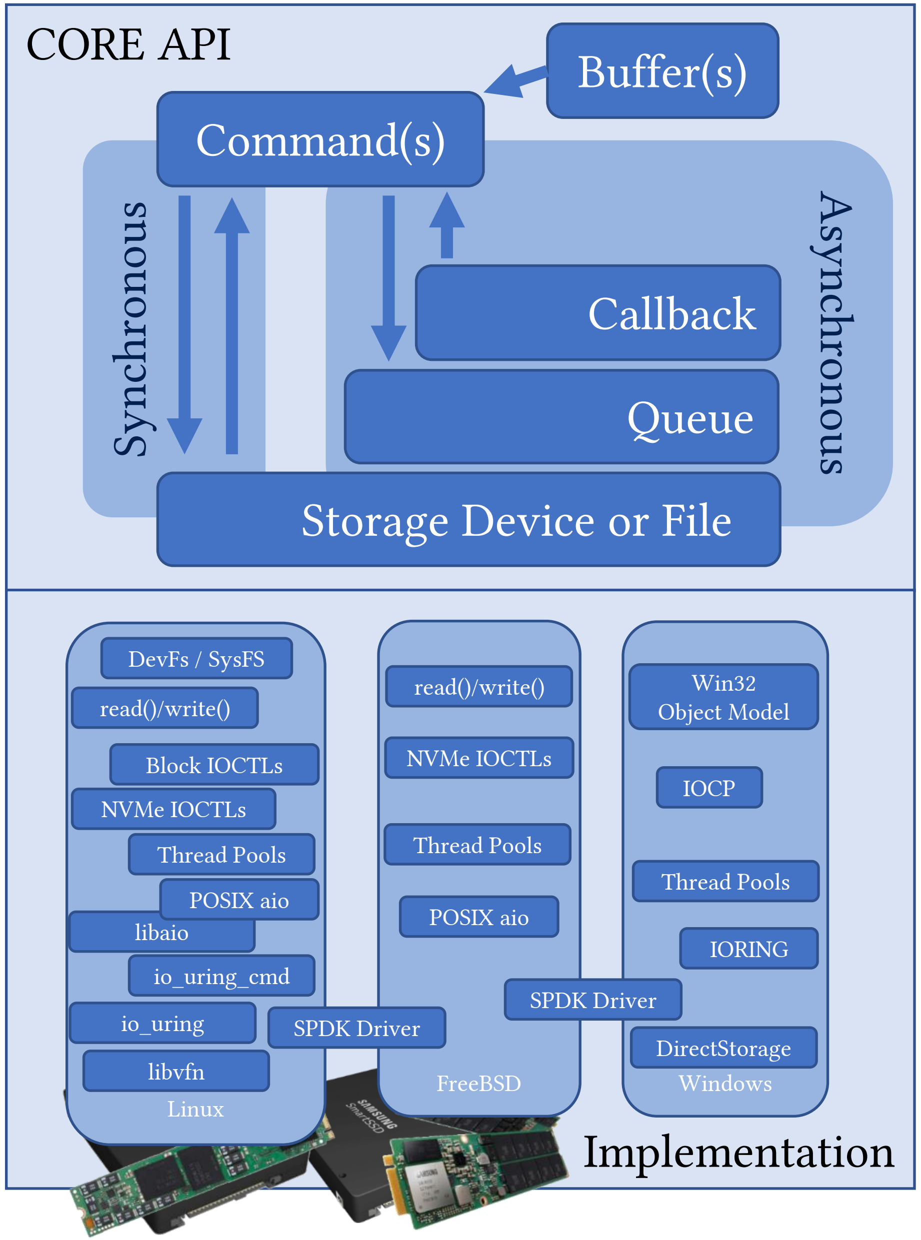


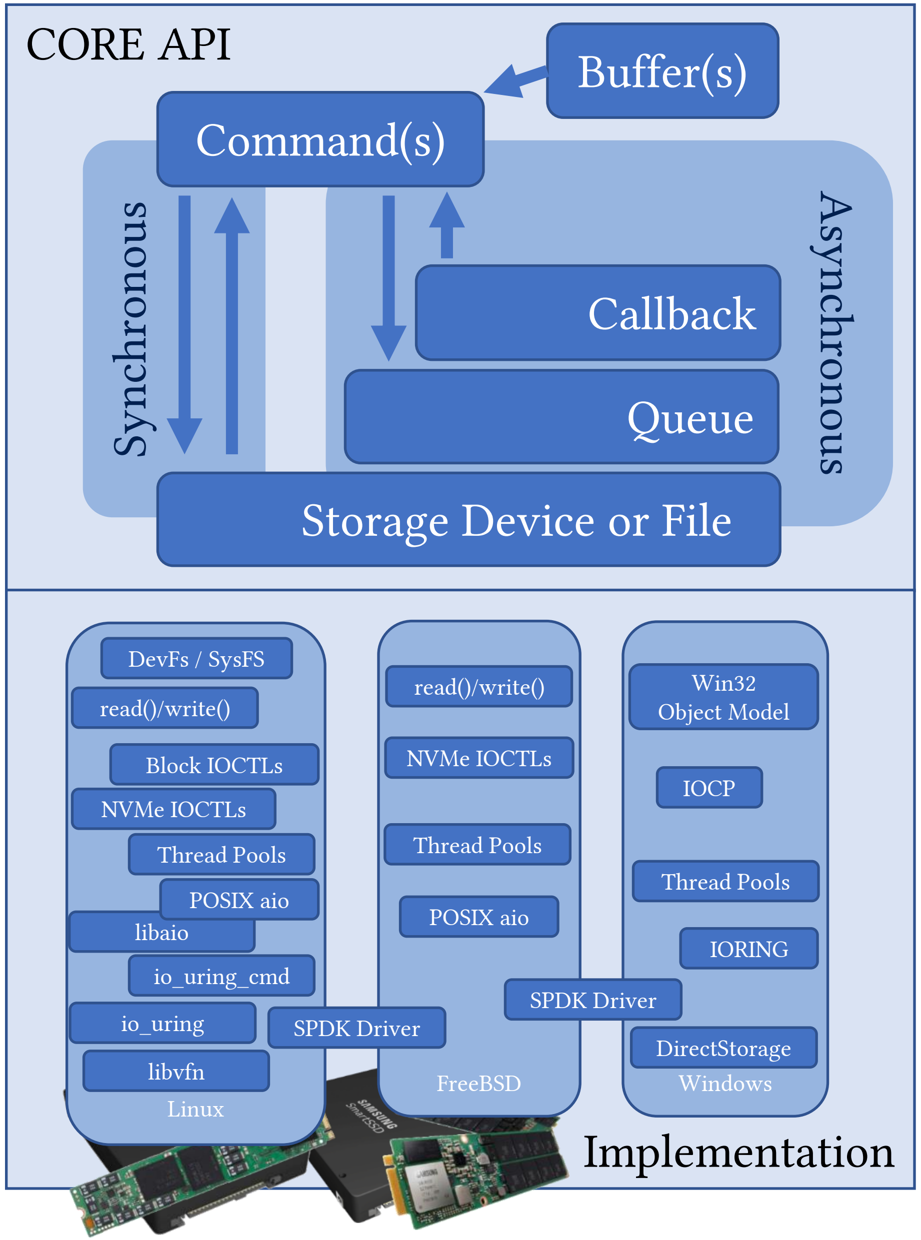
I/O Interface Independence with **xNVMe**: API

- **Buffers**



I/O Interface Independence with **xNVMe**: API

- **Buffers**
  - Contigous (`* void`)



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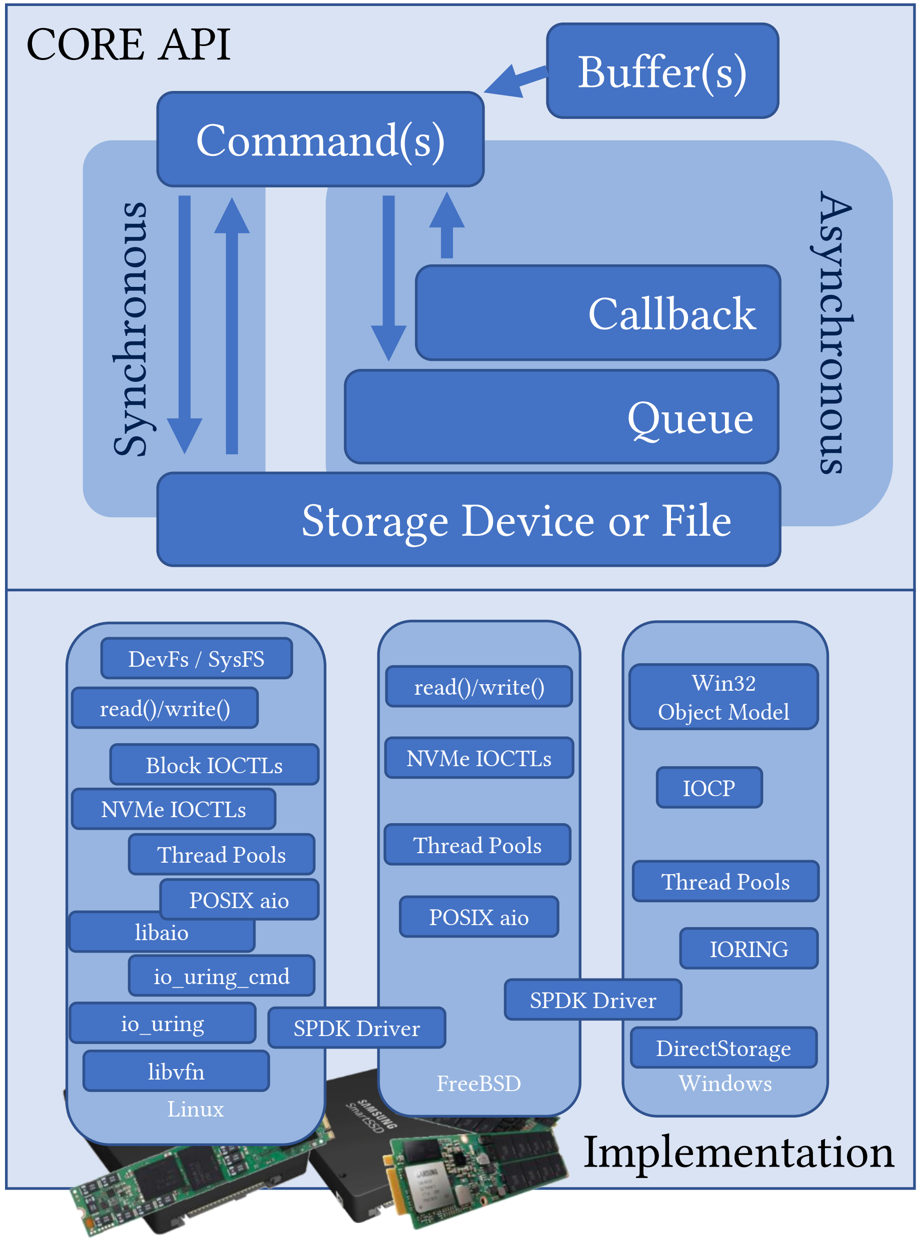
  - Vectored (`struct iovec`)



I/O Interface Independence with **xNVMe:** API

- **Buffers**
  - Contigous (`* void`)
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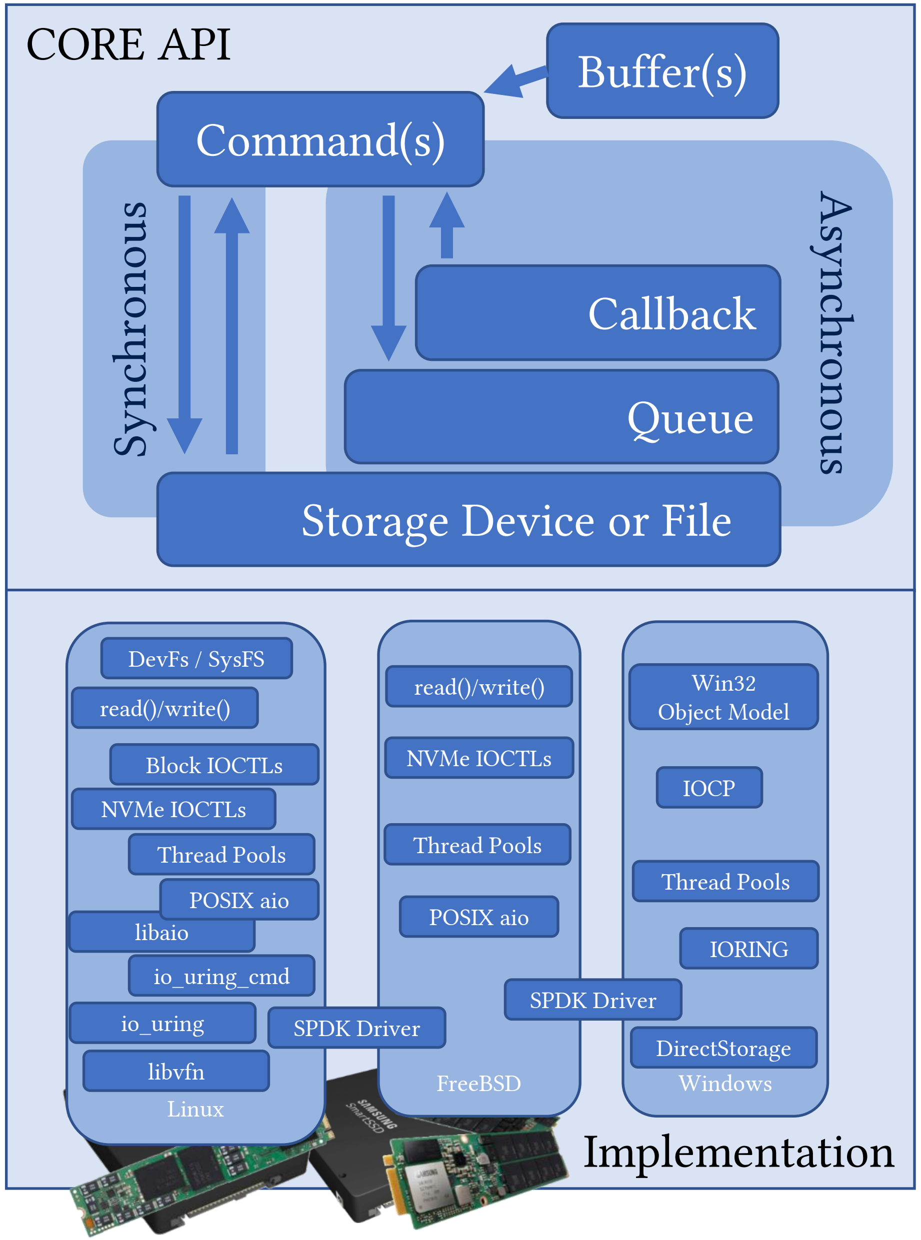
  - `**buf** = xnvme_buf_alloc(**dev**, nbytes)`

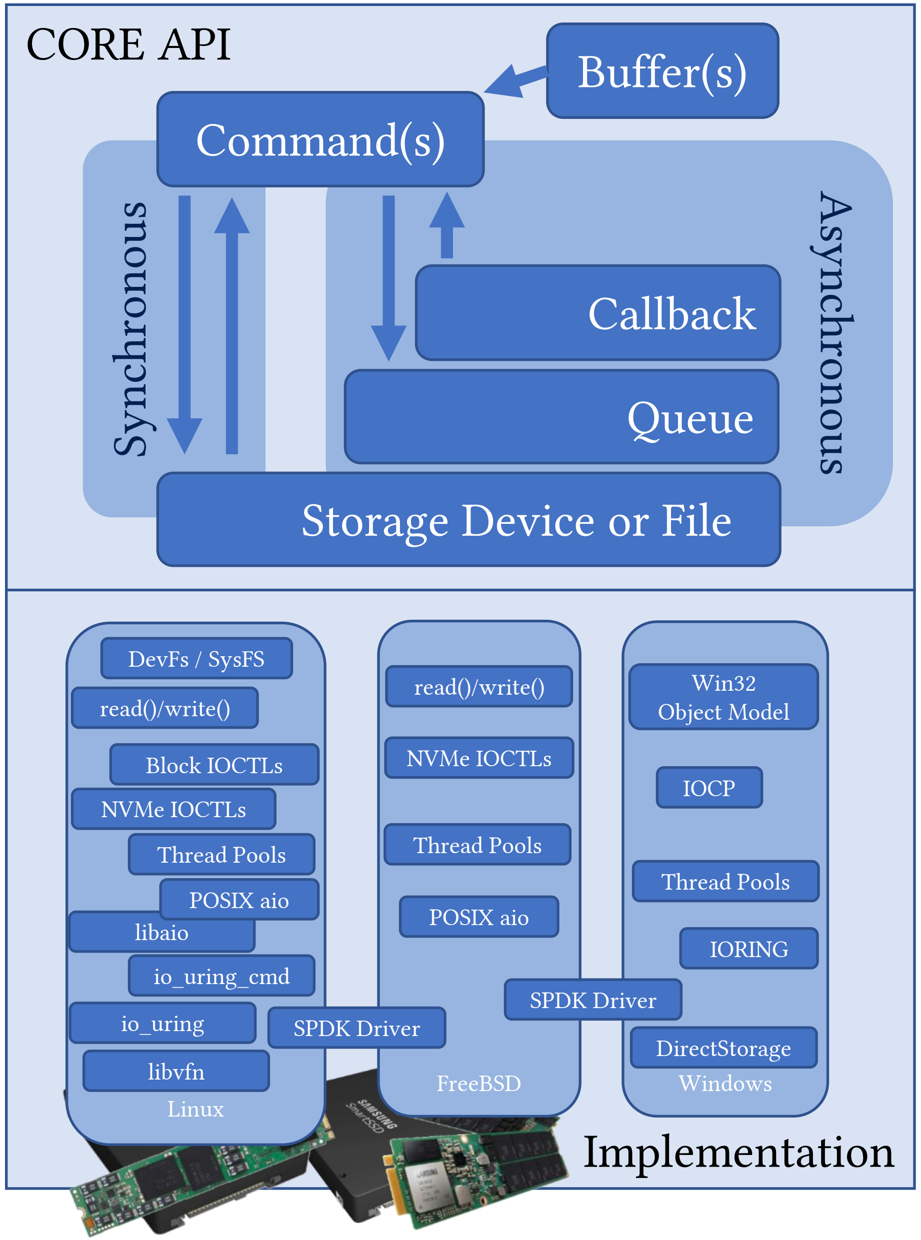


I/O Interface Independence with **xNVMe**: API

- **Buffers**
  - Contigous (`* void`)
  - Vectored (`struct iovec`)
  - **`buf`** `= xnvme_buf_alloc(`**`dev`**`, nbytes)`

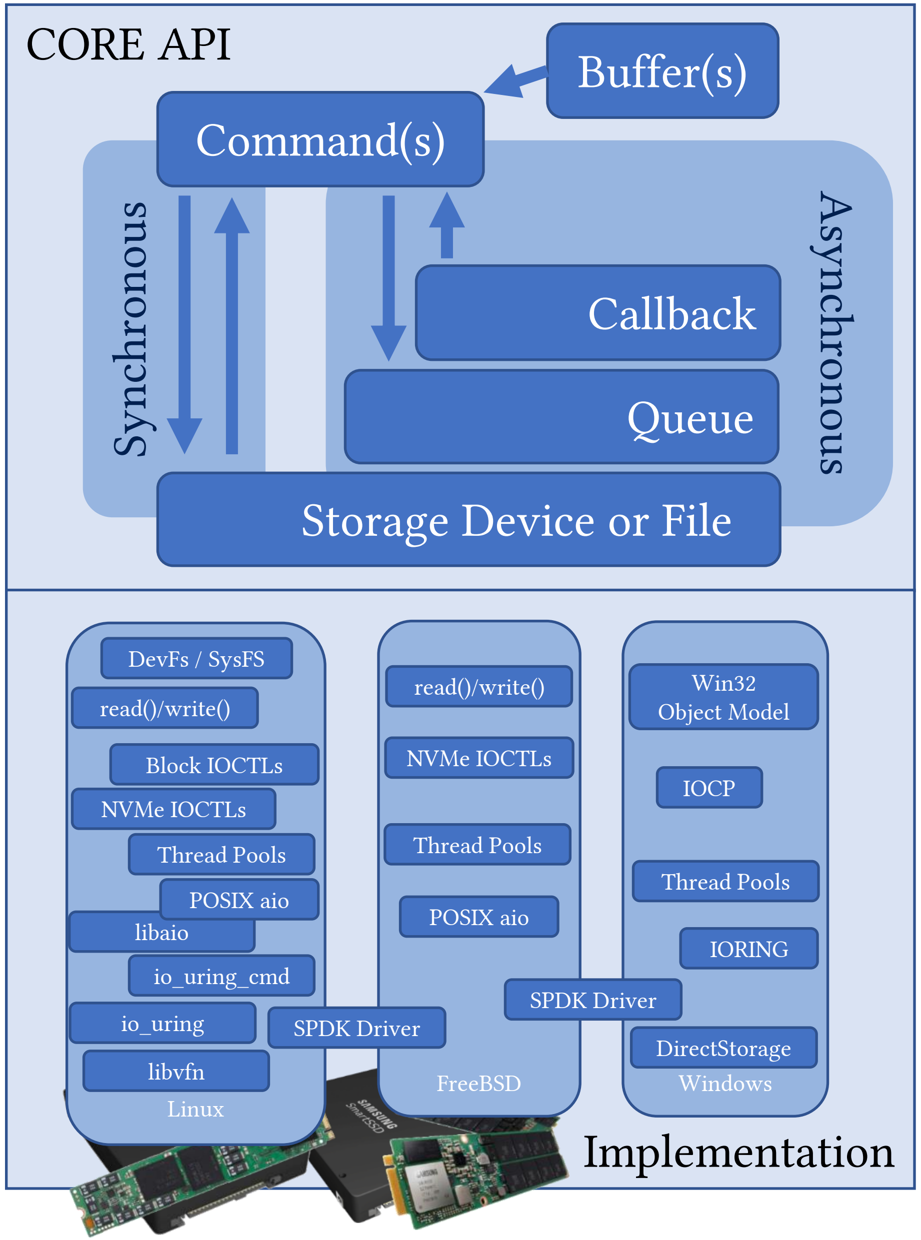
Ensure alignment constraints are met
- Page-alignment requirements for I/O interface and platform
- For I/O with given **dev**

Ensure correct memory allocator is used
- Virtual memory for OS managed
- DMA transferable for User Space NVMe Driver(s)



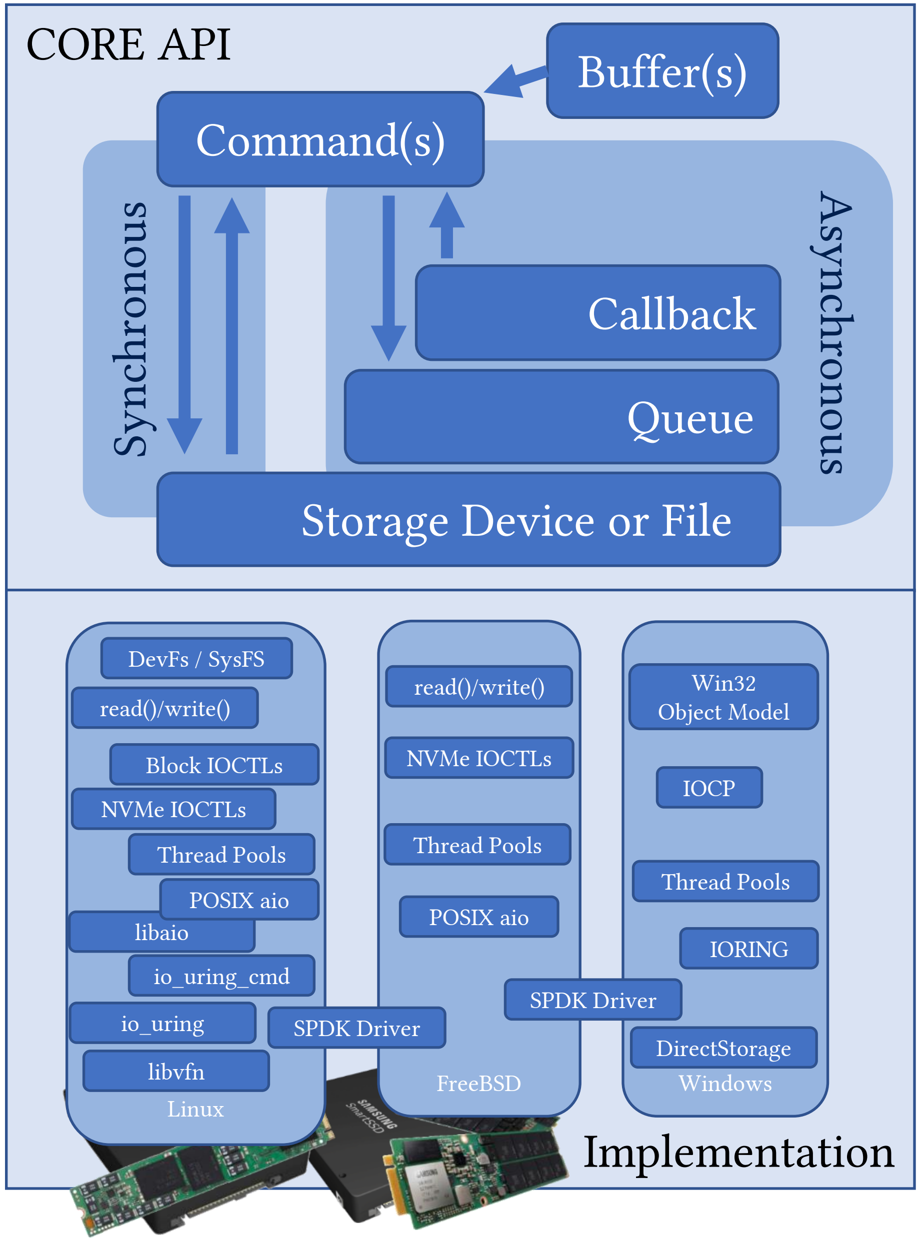
I/O Interface Independence with **xNVMe**: API

- Device Handles
- Buffers
- **Commands**
  - Synchronous
  - Asynchronous



I/O Interface Independence with **xNVMe**: API

- **Commands**
  - `xnvme_cmd_passv(ctx, vec[], ...)`
  - `xnvme_cmd_pass(ctx, **buf**, ...)`



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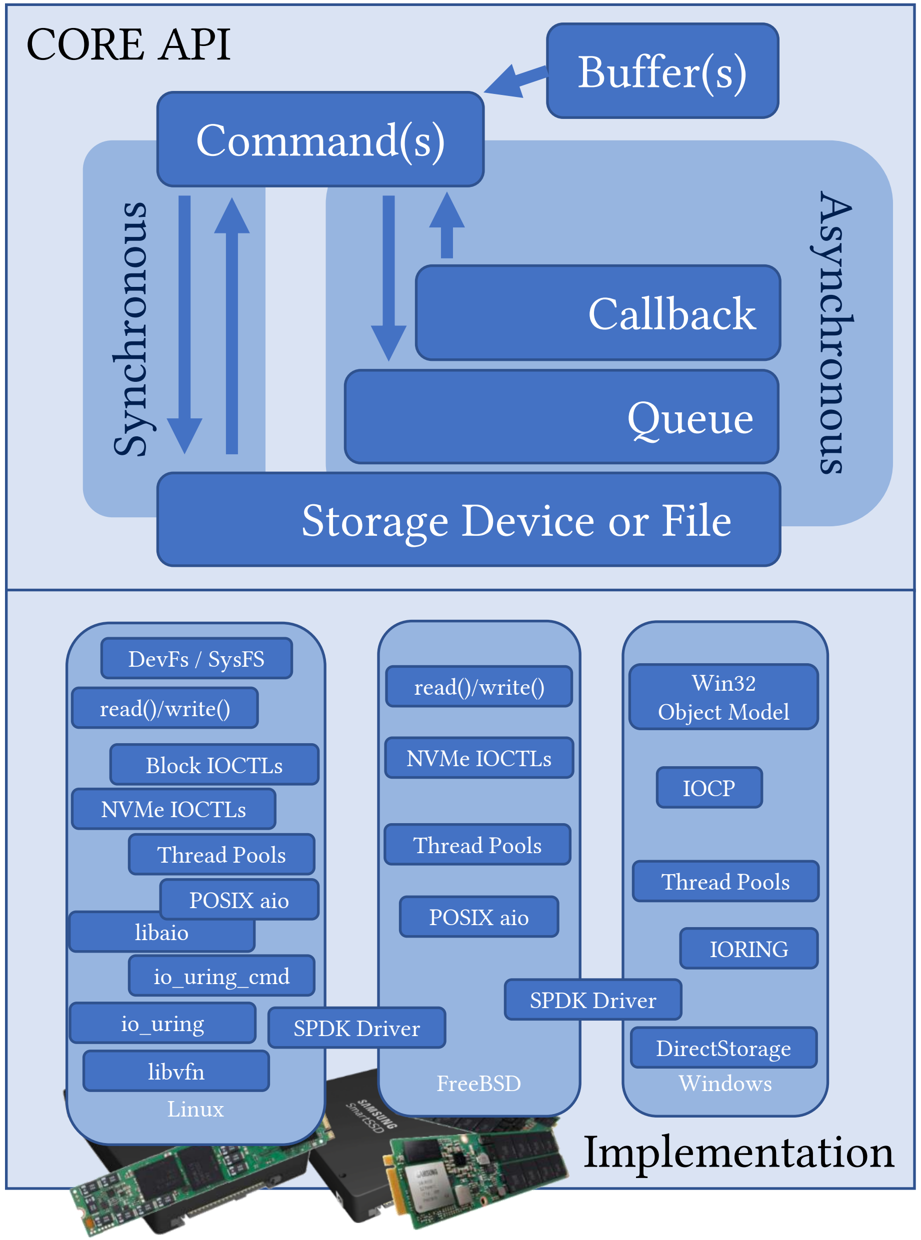

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  - NVMe Command/Completion (sqe/cqe)
  - Auxilary Information (Device & I/O path)

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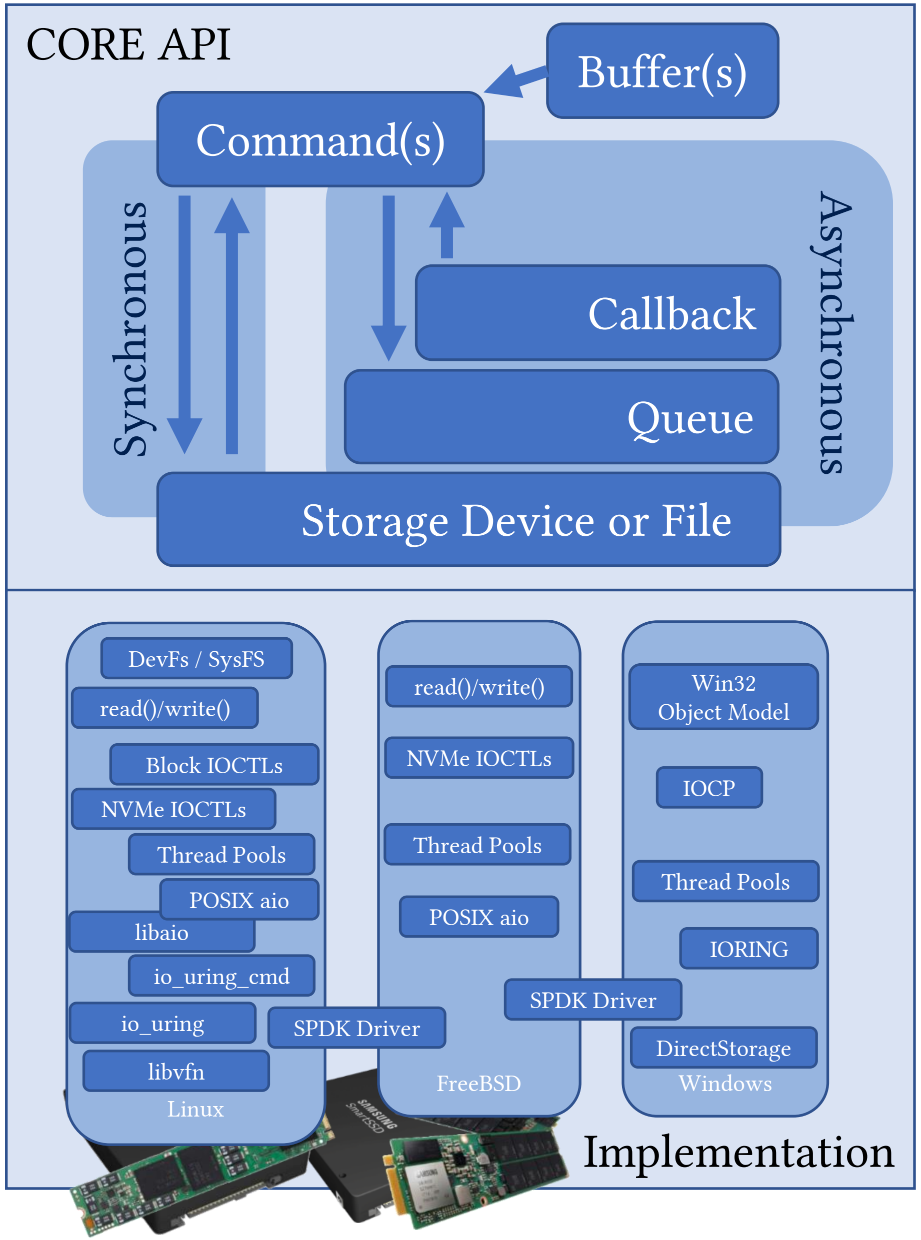

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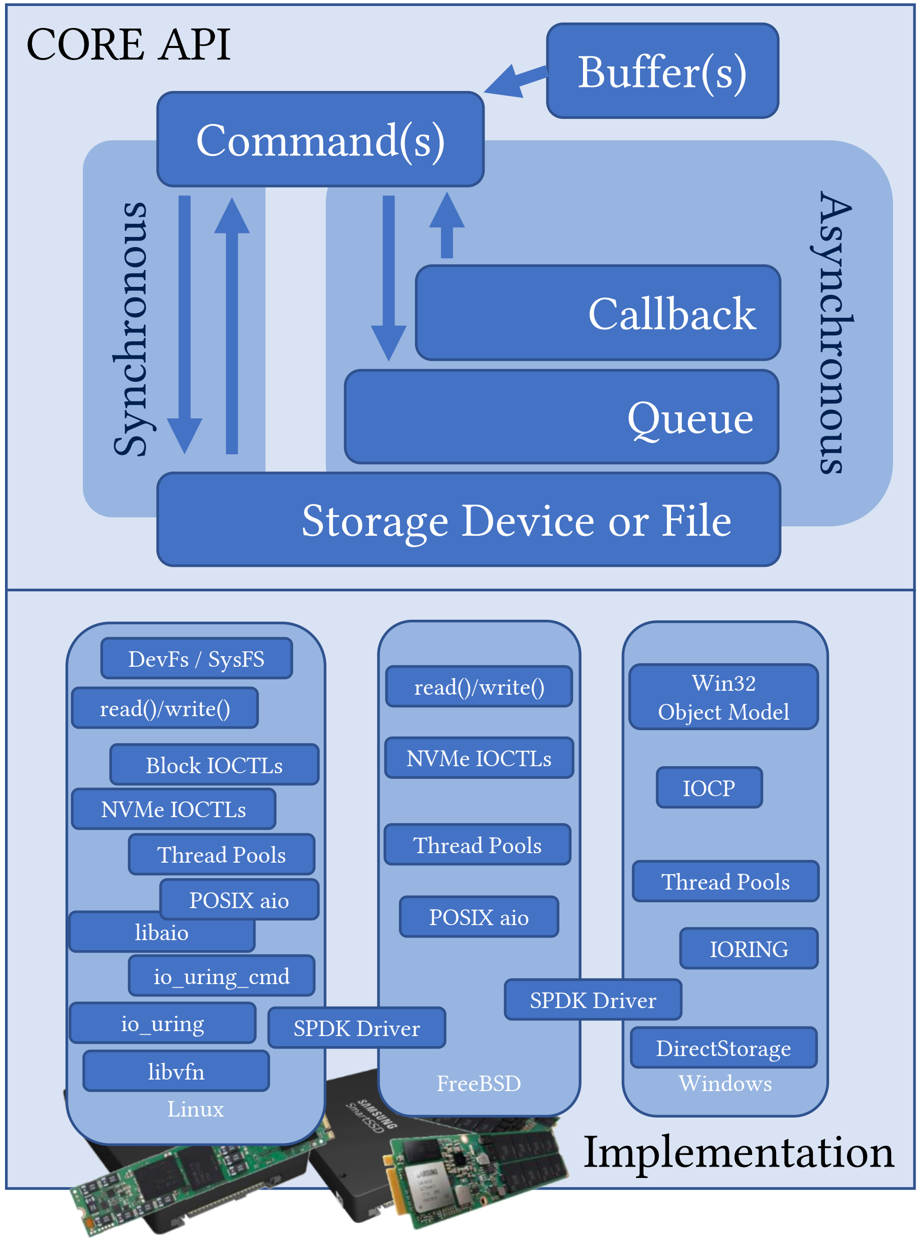
```
int
xnvme_znd_append(struct xnvme_cmd_ctx *ctx, uint32_t nsid, uint64_t zslba,
                 uint16_t nlb, const void *dbuf, const void *mbuf)
{
        void *cdbuf = (void *)dbuf;
        void *cmbuf = (void *)mbuf;

        size_t dbuf_nbytes = cdbuf ? ctx->dev->geo.lba_nbytes * (nlb + 1) : 0;
        size_t mbuf_nbytes = cmbuf ? ctx->dev->geo.nbytes_oob * (nlb + 1) : 0;

        ctx->cmd.common.opcode = XNVME_SPEC_ZND_OPC_APPEND;
        ctx->cmd.common.nsid = nsid;
        ctx->cmd.znd.append.zslba = zslba;
        ctx->cmd.znd.append.nlb = nlb;

        return xnvme_cmd_pass(ctx, cdbuf, dbuf_nbytes, cmbuf, mbuf_nbytes);
}
```



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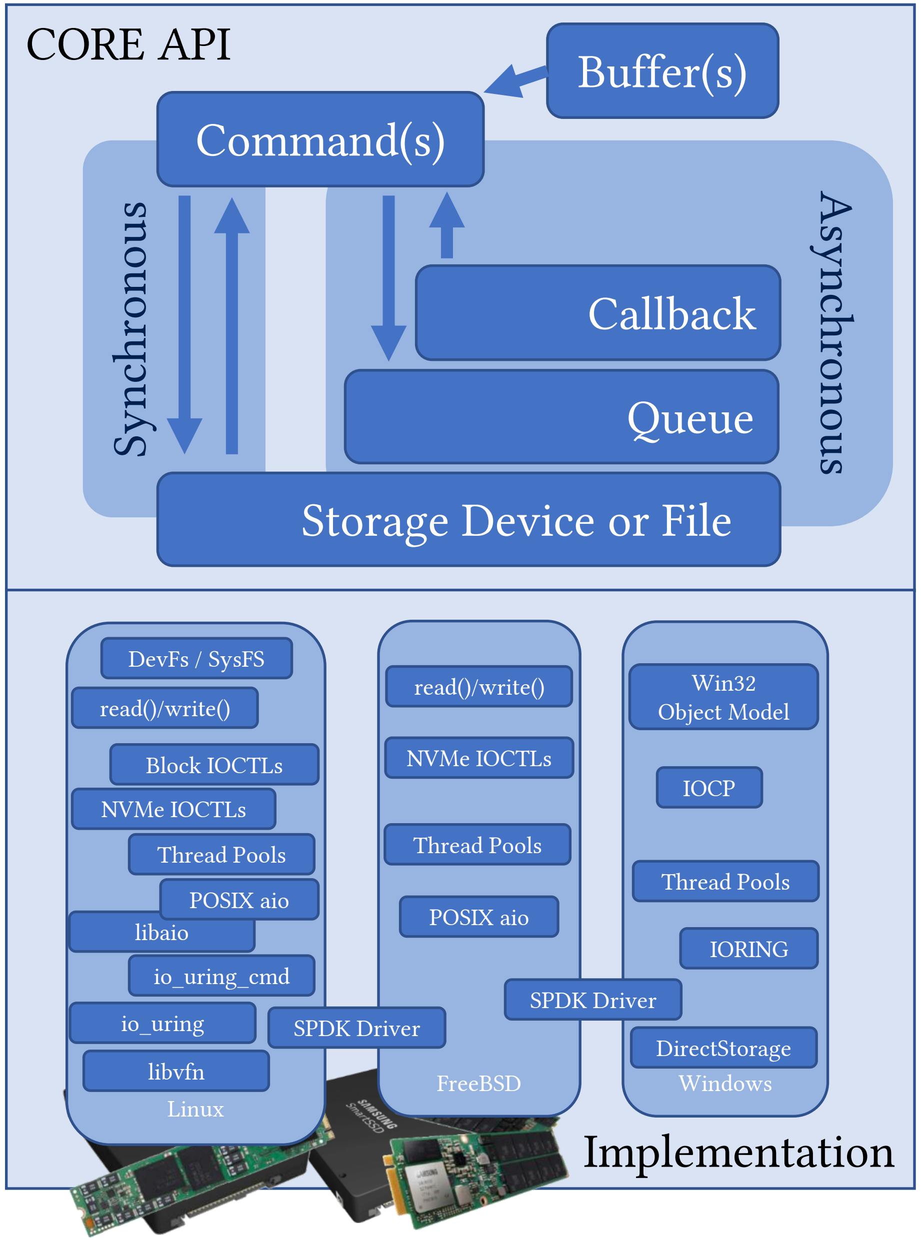
  - NVMe Command/Completion (sqe/cqe)
  - Auxilary Information (Device & I/O path)
- **Synchronous**

```
ctx = xnvme_cmd_ctx_from_dev(dev)
  ... setup ctx.cmd (sqe) ...
```



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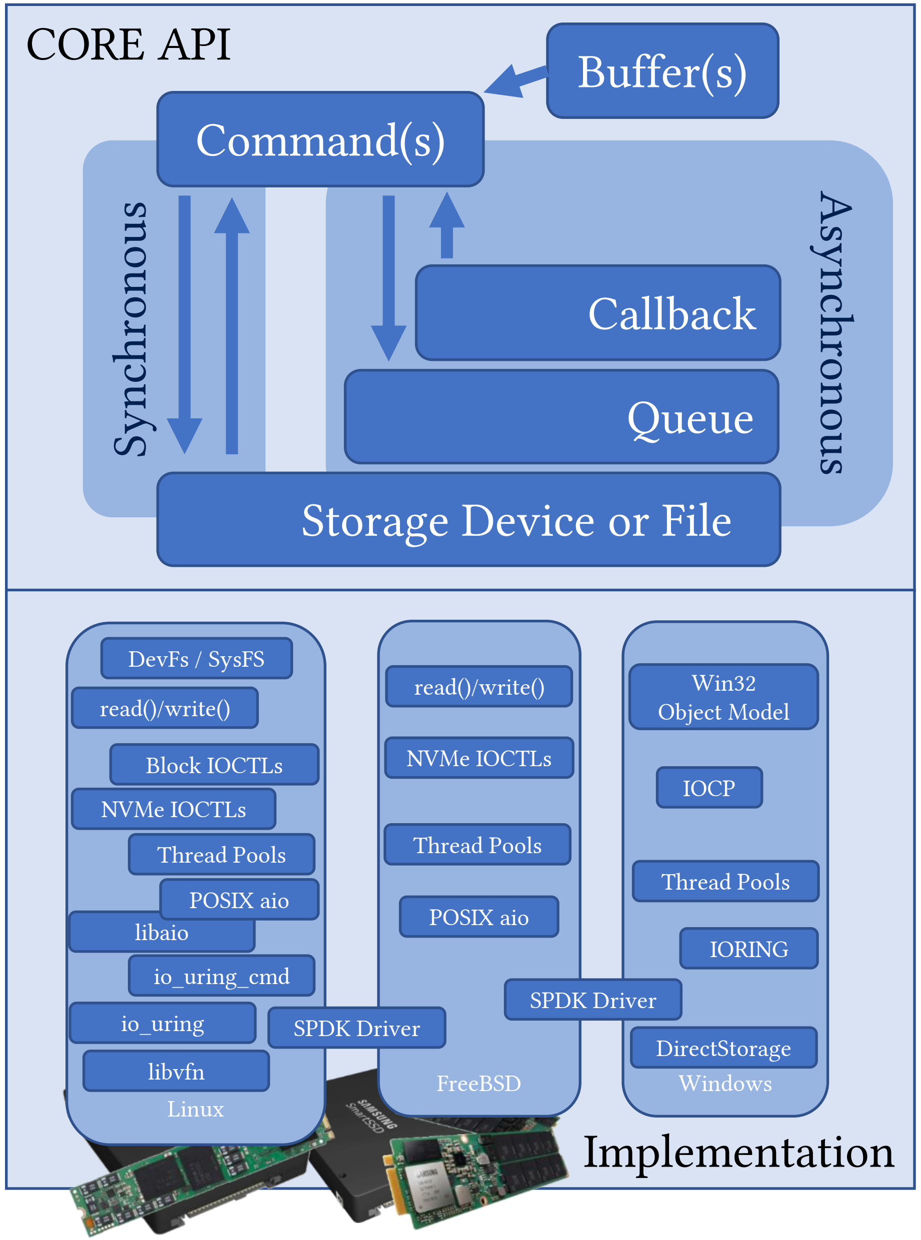

I/O Interface Independence with **xNVMe**: API

- Device Handles
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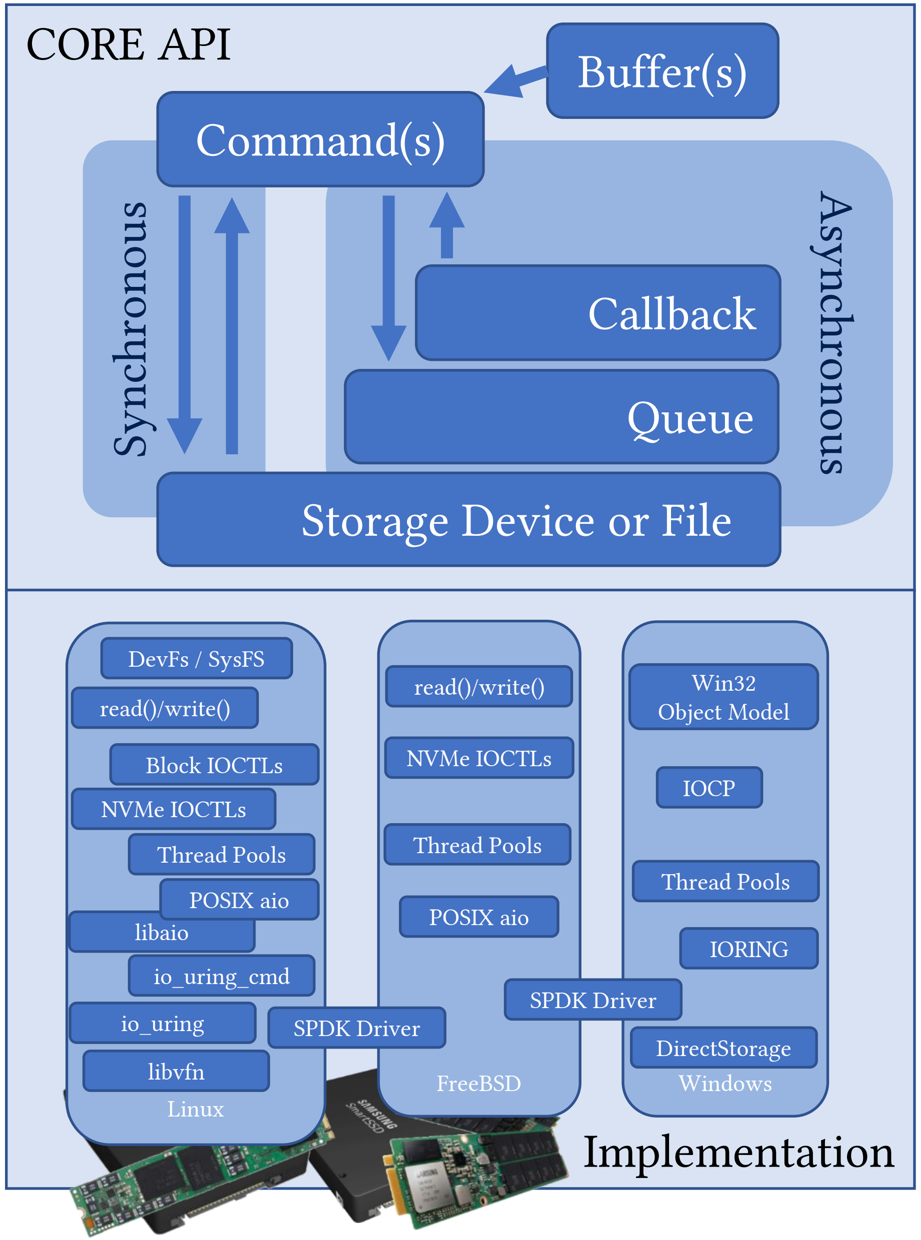

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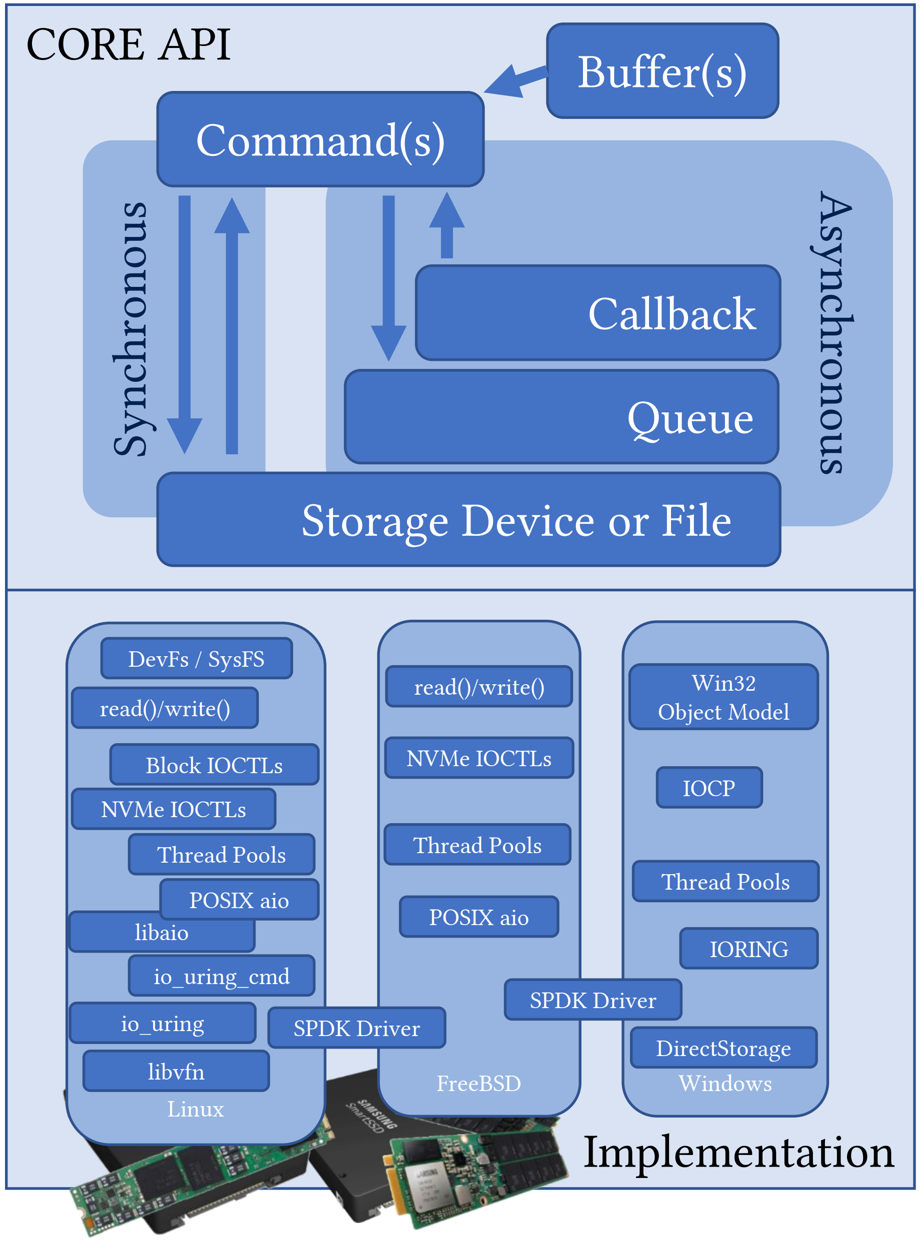

I/O Interface Independence with **xNVMe**: API

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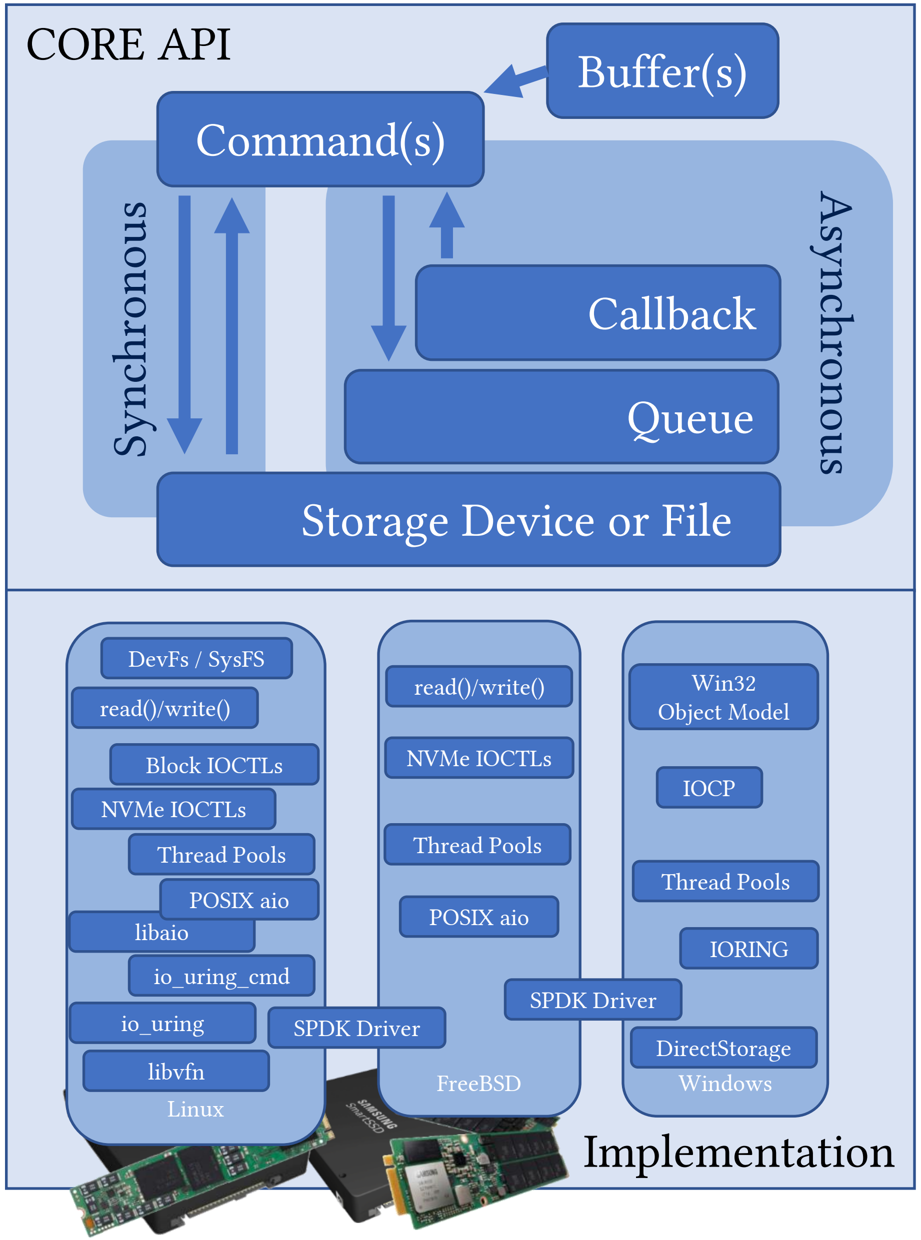
```
xnvme_queue_init(dev, cap, **q, ..)
```



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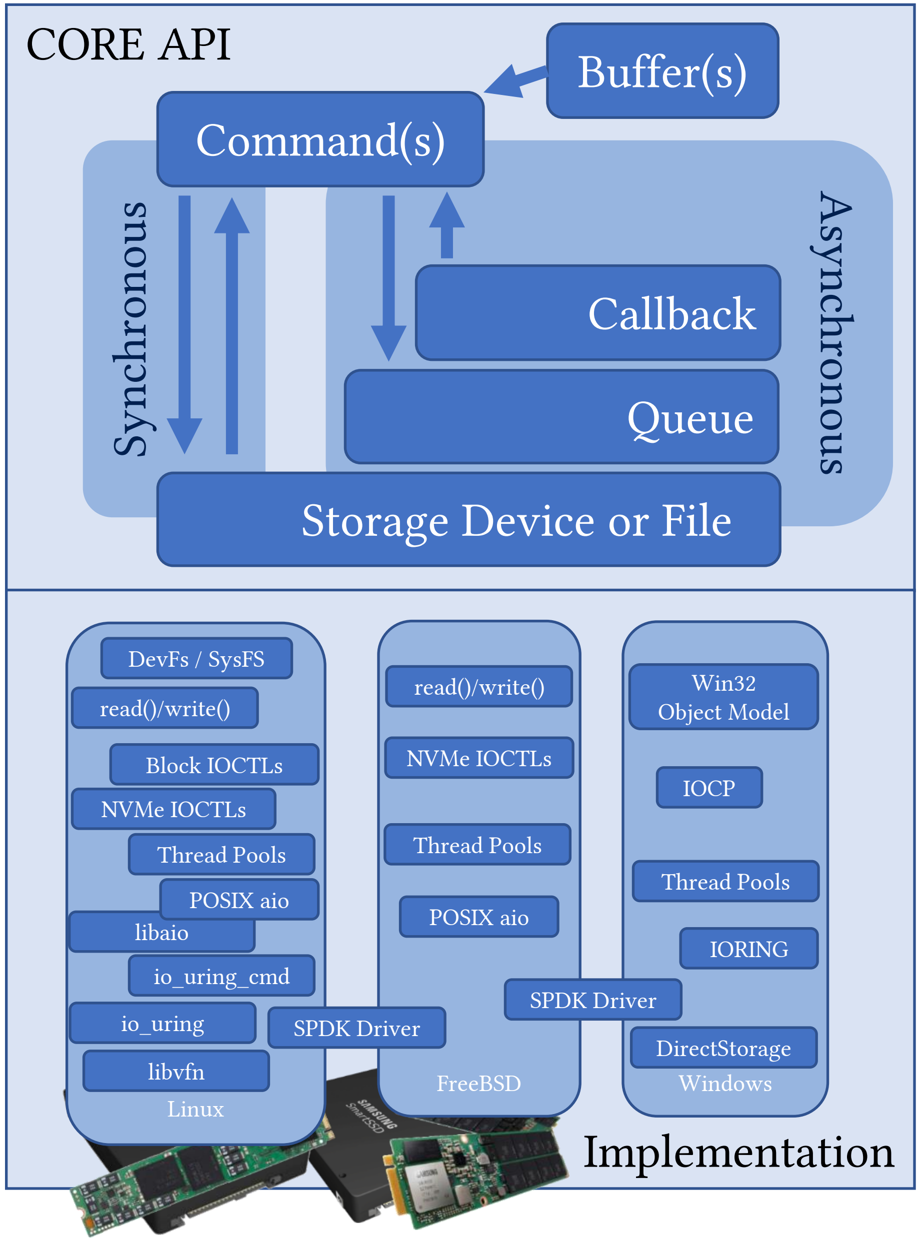

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xnvme_queue_poke(q, max)
xnvme_queue_drain(q)
```

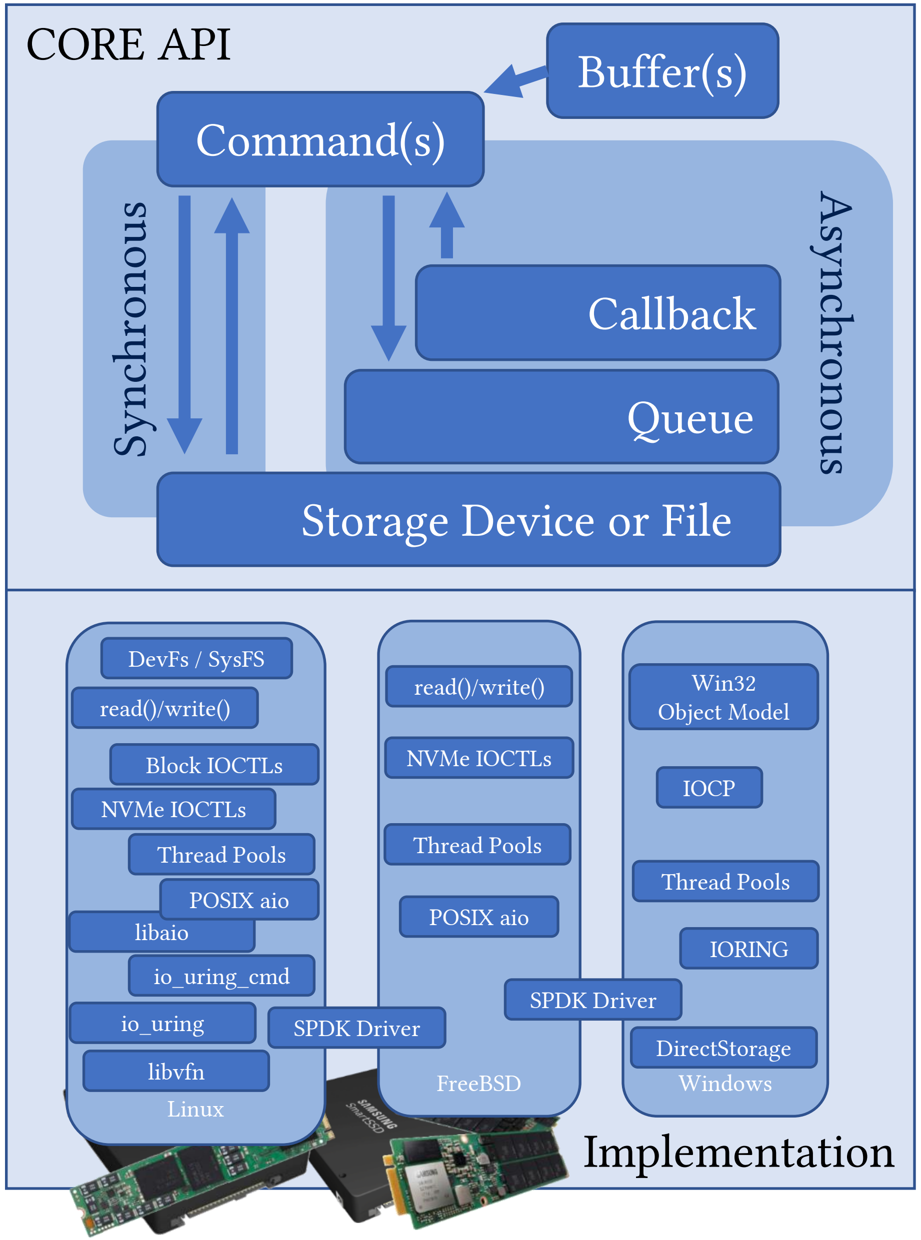

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Process at most **max** completions

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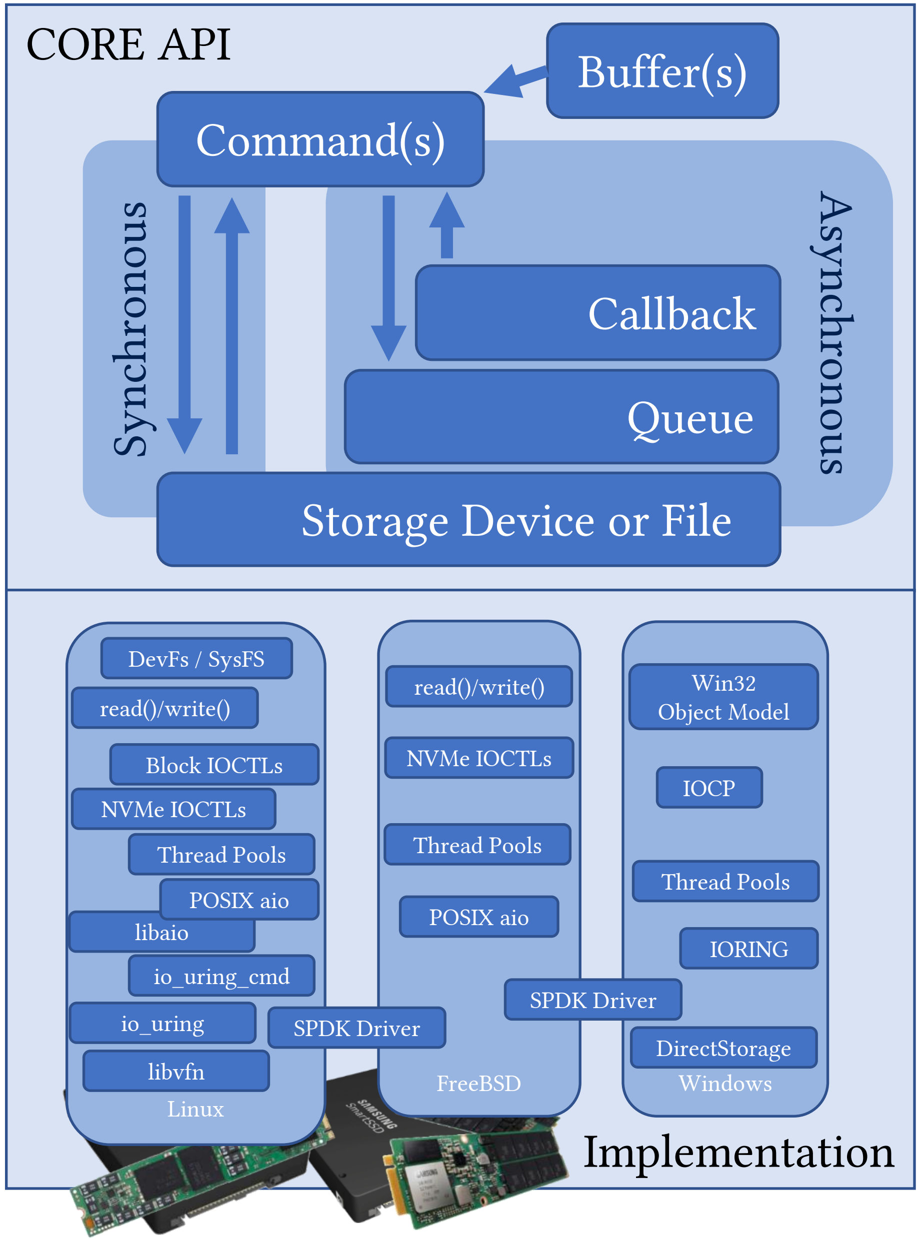

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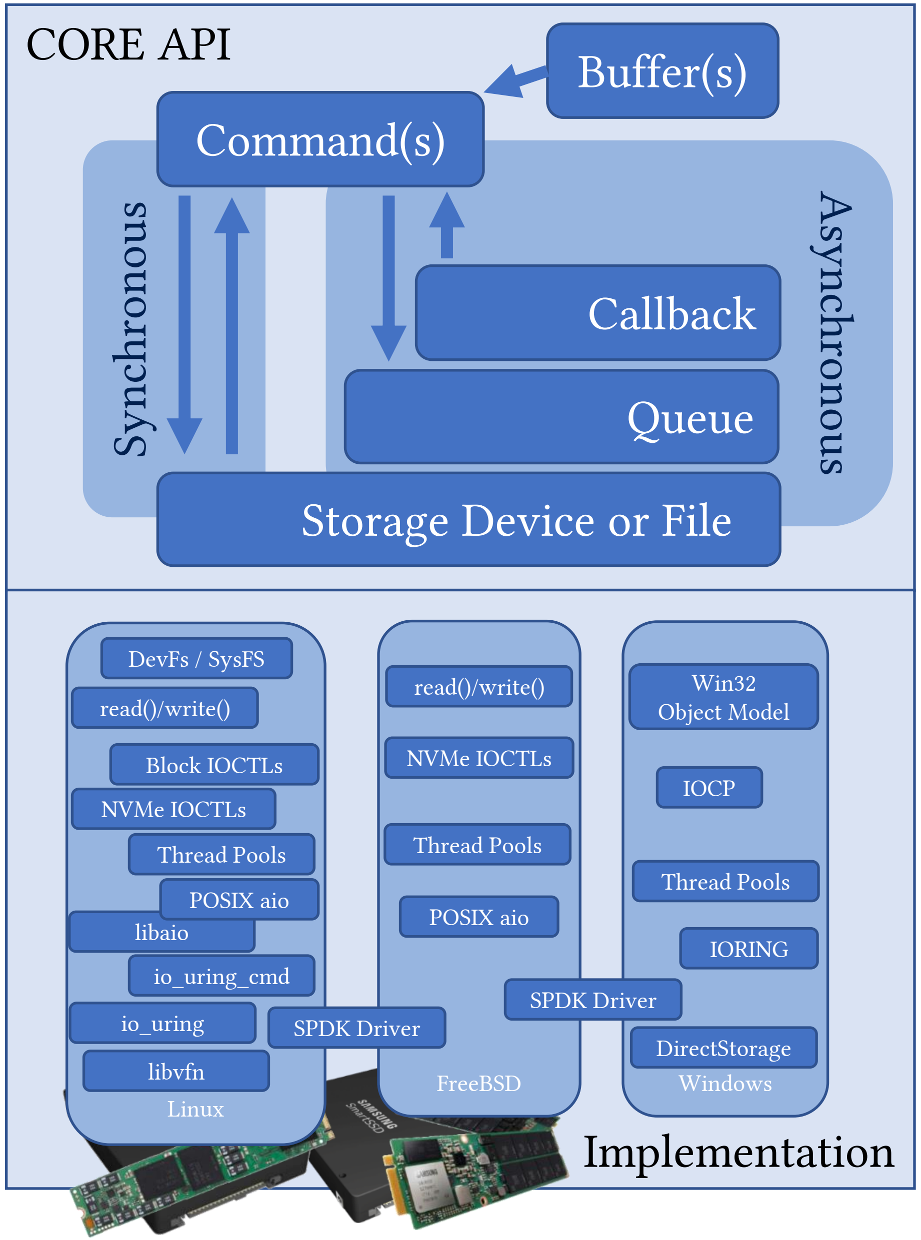
xnvme_cmd_pass(ctx, buf, ...)
```

Process at most **max** completions

```
xnvme_queue_poke(q, max)

   ctx.callback(ctx, ctx.args)
     ... inspect ctx.cpl (cqe) ...
```



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ctx = xnvme_cmd_ctx_from_queue(q)
  ... setup ctx.cmd (sqe) ...
xnvme_cmd_pass(ctx, buf, ...)
```
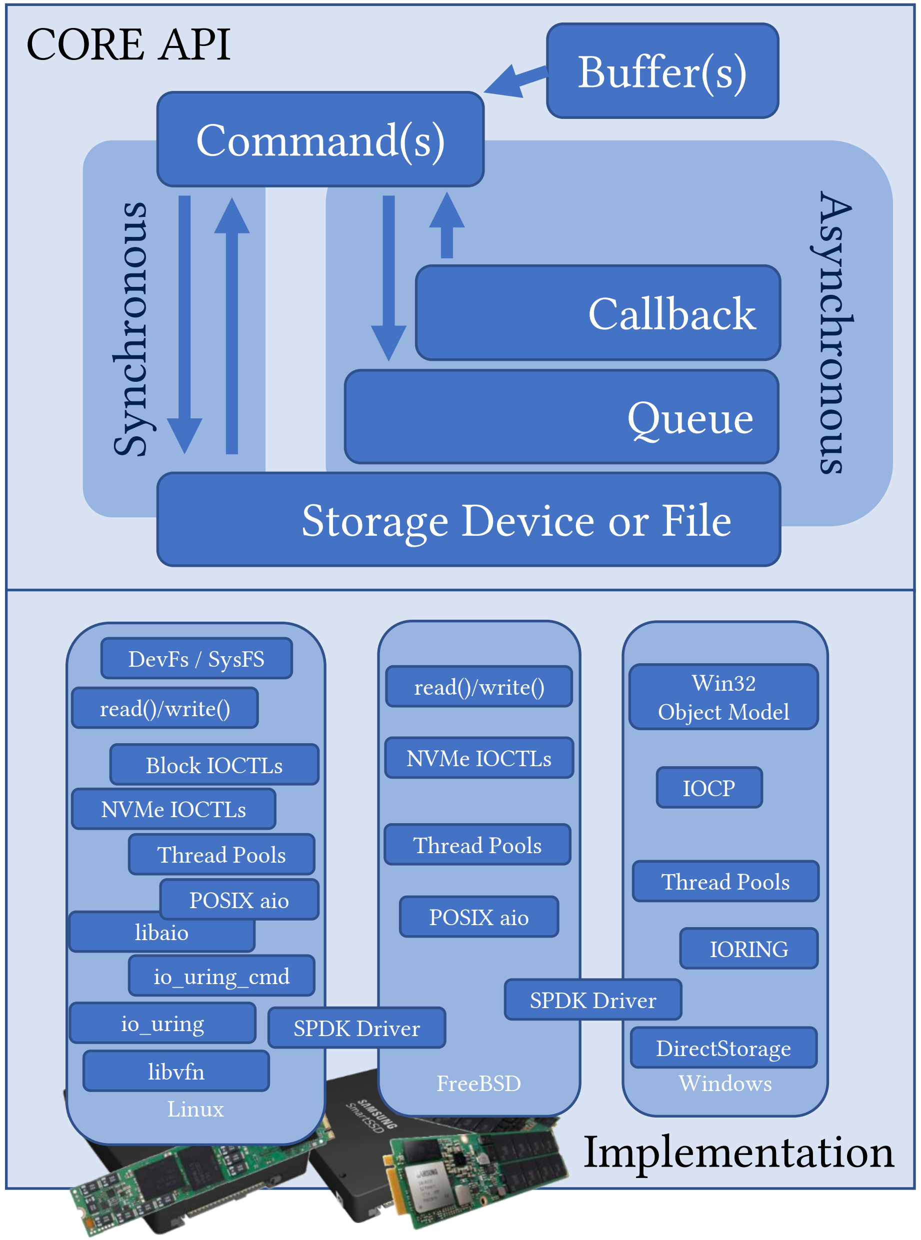

Process at most **max** completions

```
xnvme_queue_poke(q, max)
xnvme_queue_drain(q)
```

Process completions until queue is **empty**

```
ctx.callback(ctx, ctx.args)
  ... inspect ctx.cpl (cqe) ...
```



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- Device Handles
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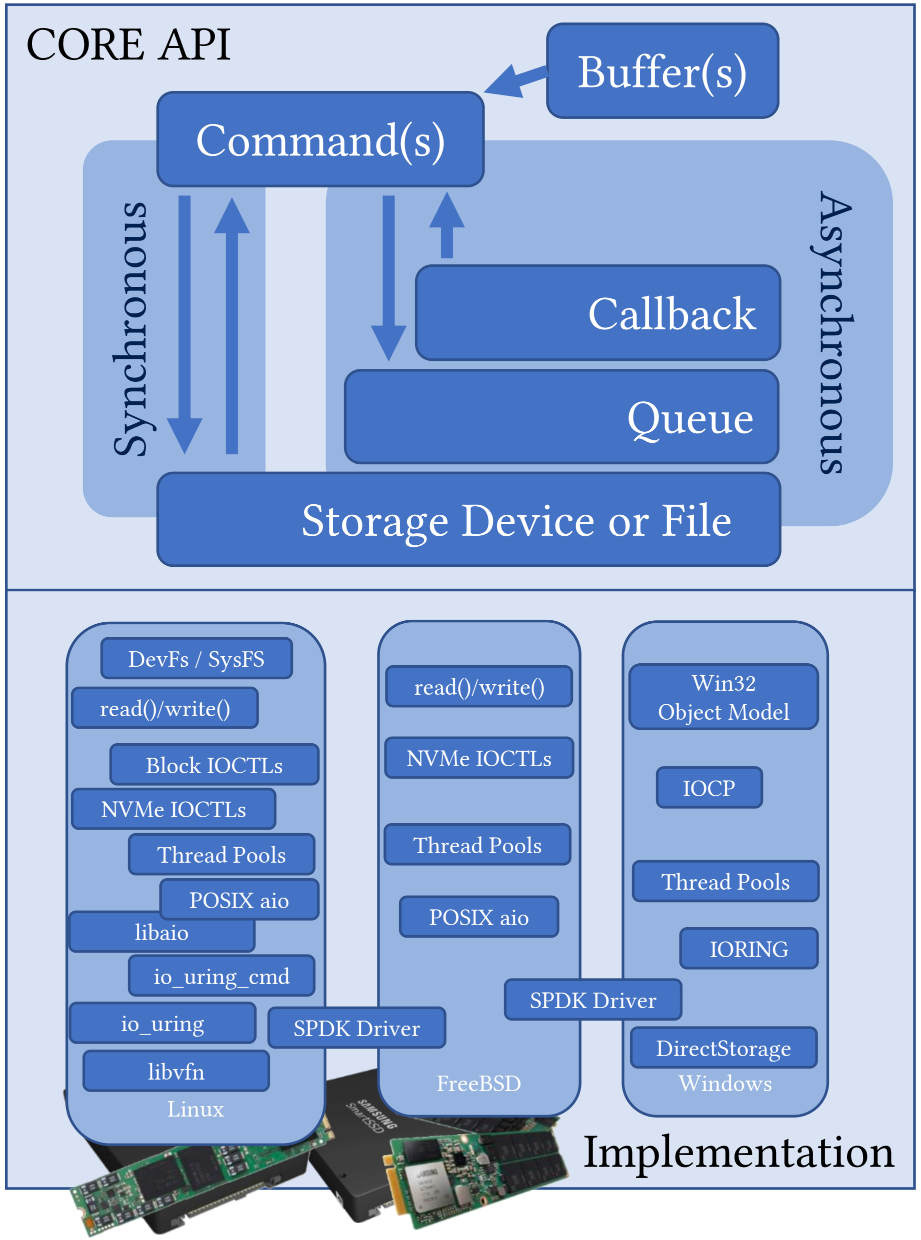

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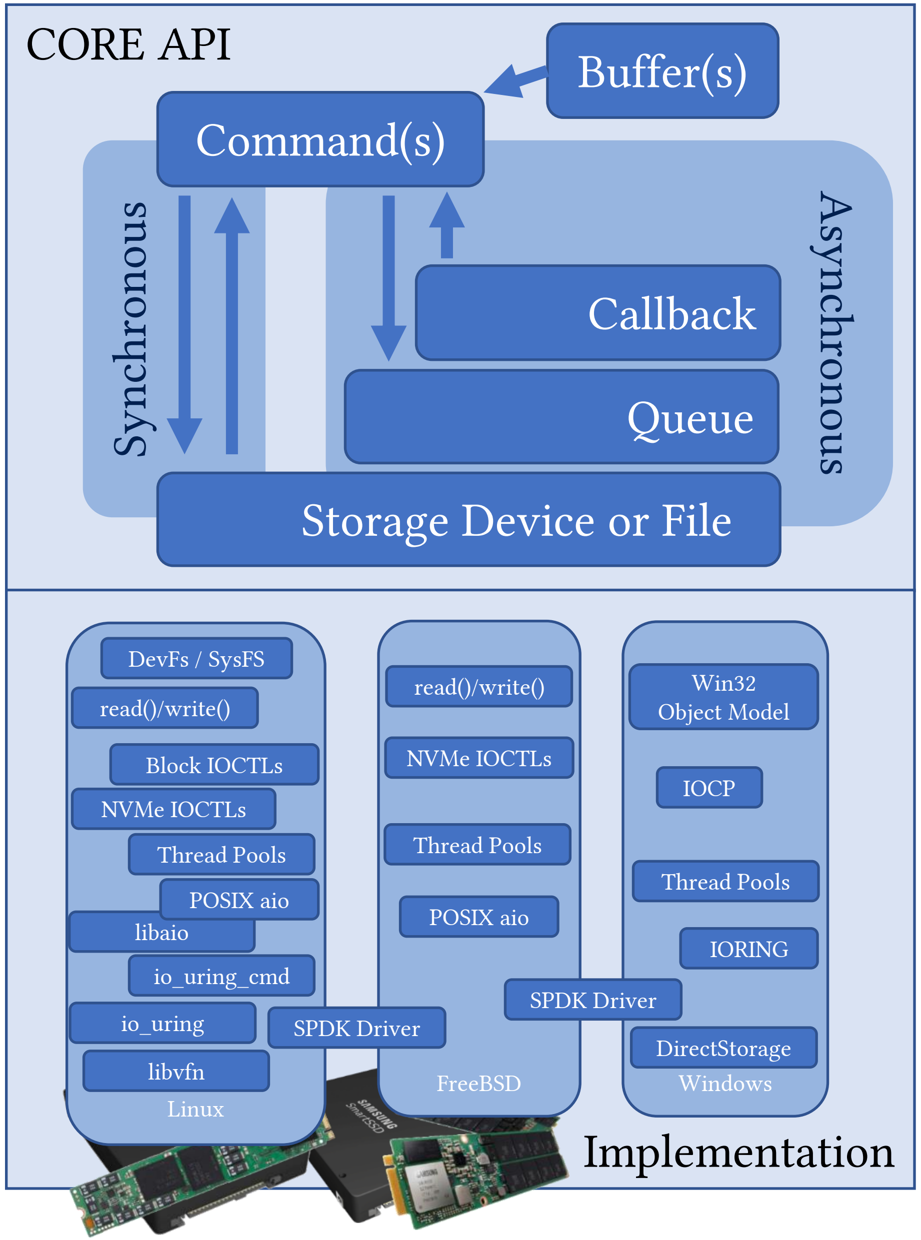

I/O Interface Independence with **xNVMe**: API

- Device Handles
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- Commands
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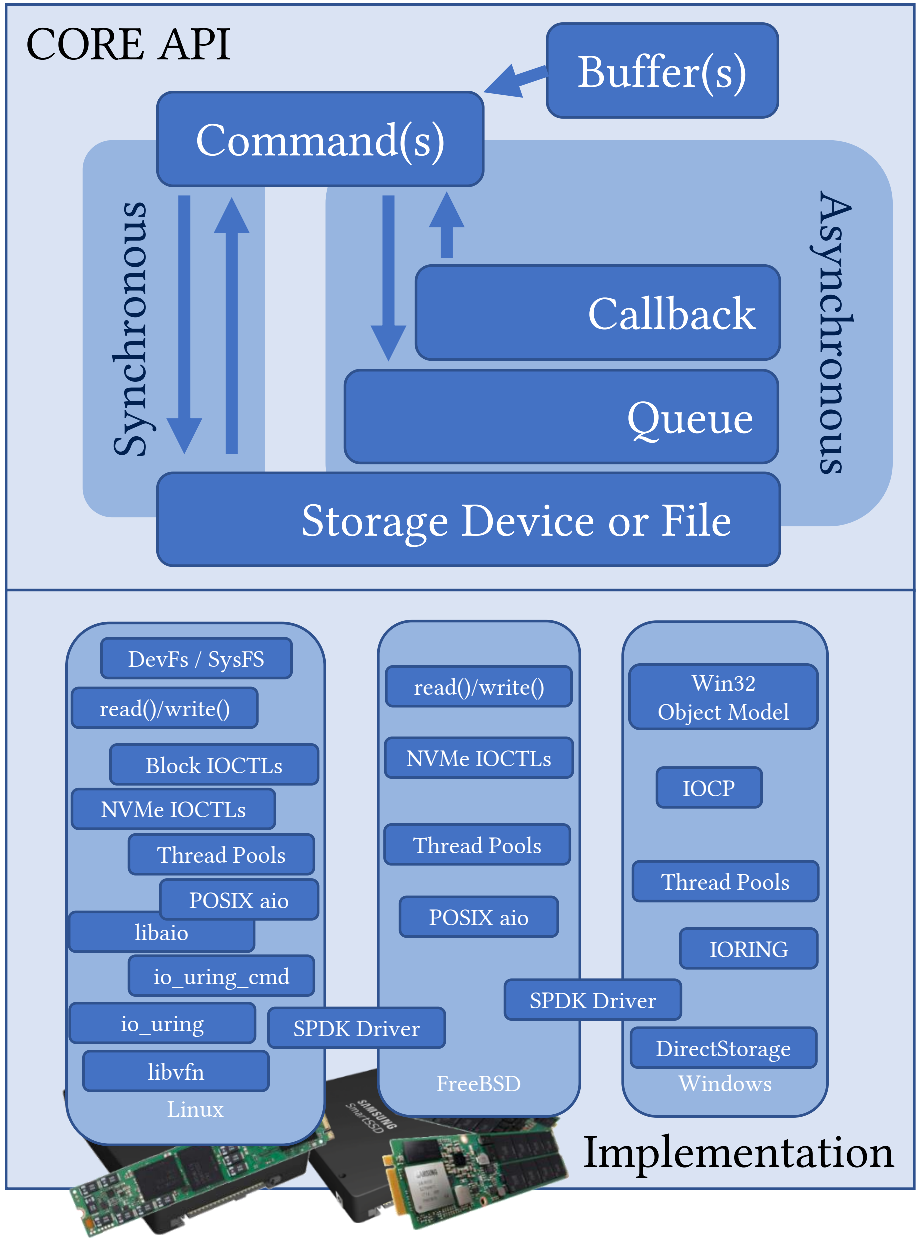
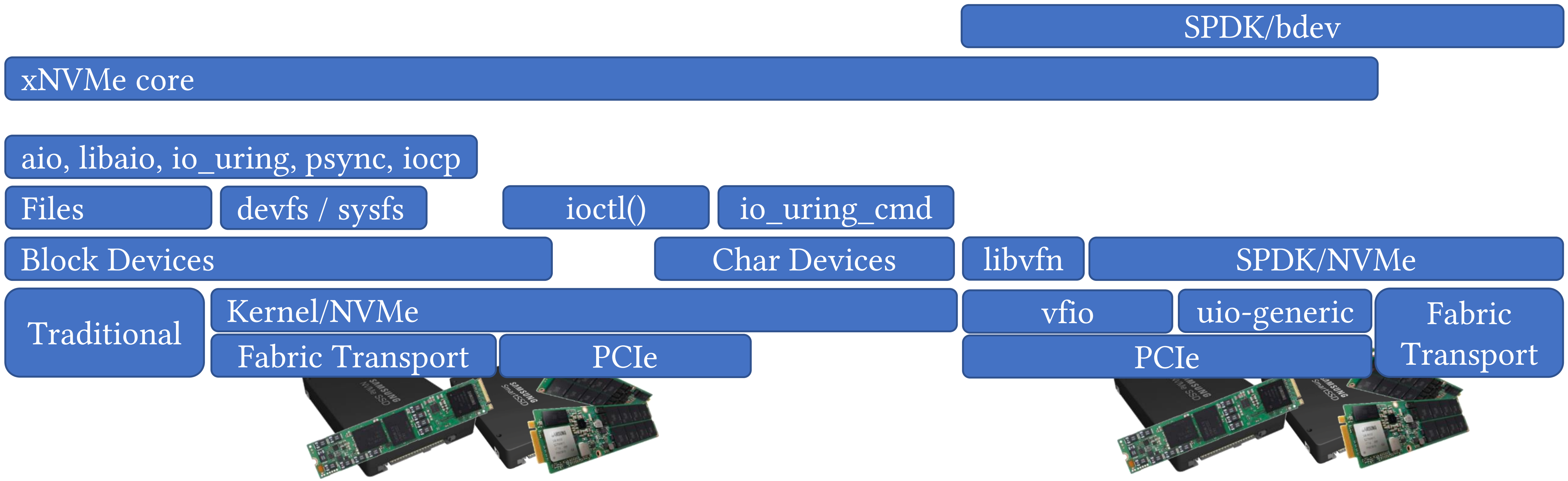
- **For details, docs are available**
  - C API
    https://xnvme.io/docs/latest/capis/
  - C API Examples
    https://xnvme.io/docs/latest/examples/



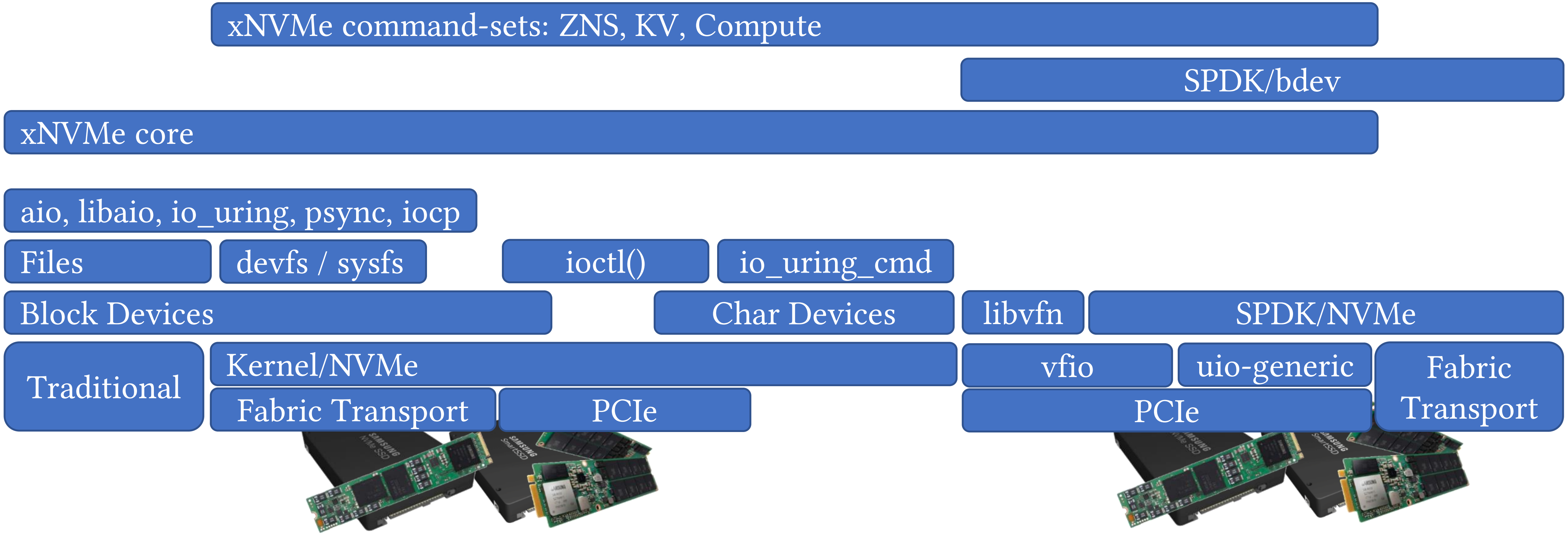
I/O Interface Independence with **xNVMe**

- A minimal encapsulation of system-interfaces and user-space drivers into a unified API for device handles, buffers, commands and their submission in synchronous and asynchronous mode



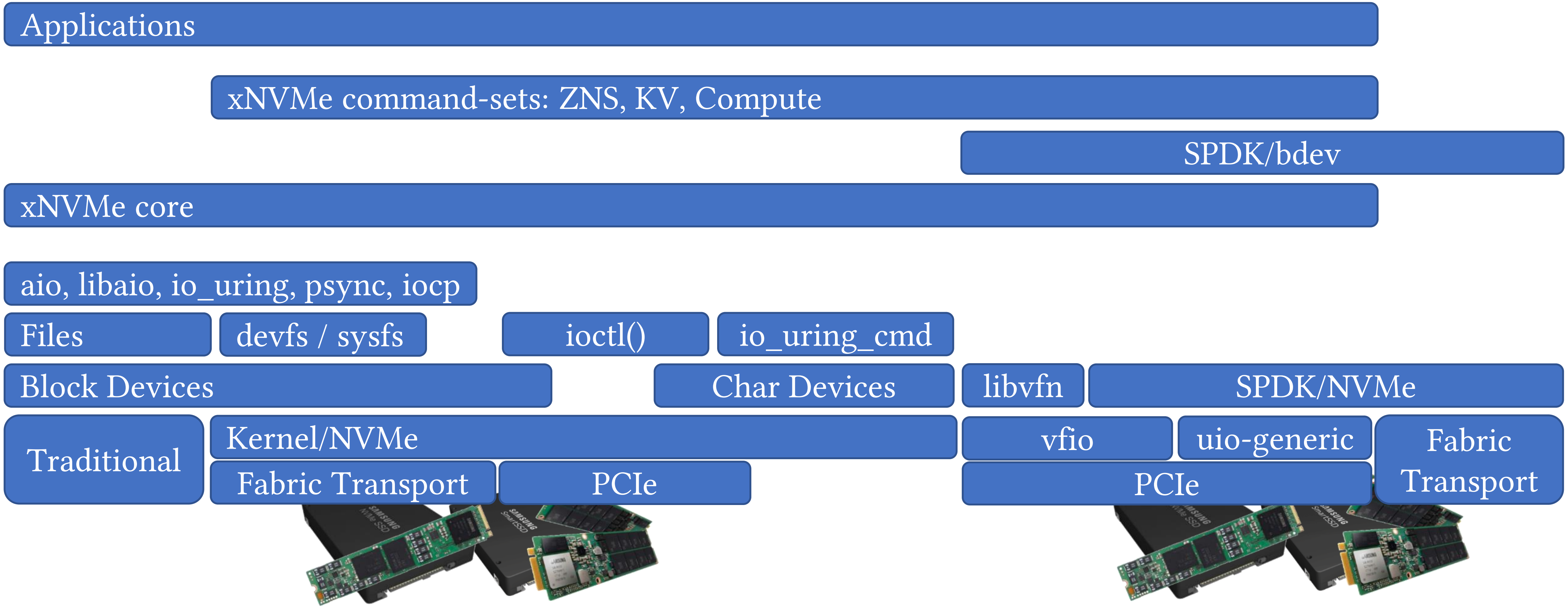
I/O Interface Independence with **xNVMe**

- **Extensibility**: a single, simple command construction



I/O Interface Independence with **xNVMe**

- **Extensibility**: a single, simple command construction
- **Applications**: use command-set helpers or directly to the core



Performance Evaluation

Performance Evaluation: framework

- Quantify performance penalty of xNVMe

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    1. **Baseline** overhead; non-I/O interface and non-device specific
    2. For each I/O **Interface** compare overhead using an NVMe device
    3. **Scalability**; for each I/O interface using an NVMe device: verify that the overhead remains constant when scaling up I/O payload size and queue-pressure

Performance Evaluation: framework

- Quantify performance penalty of xNVMe
- Commodity hardware for **reproducibility**

Hardware	Model
CPU	Intel Core i5-9400 2.9Ghz
Memory	Corsair 2x 16GB DDR4 3200Mhz CL18
Board	MSI MPG Z390I Gaming Edge AC
SSD	Intel Optane Memory M10 Series (MEMPEK1J016GAL)
Software	**Model**
FreeBSD	Version 12.1
fio	Version 3.27
gcc	Version 10.2.1
clang	Version 12.0.1
SPDK	Version 21.04
xNVMe	Version 0.0.26

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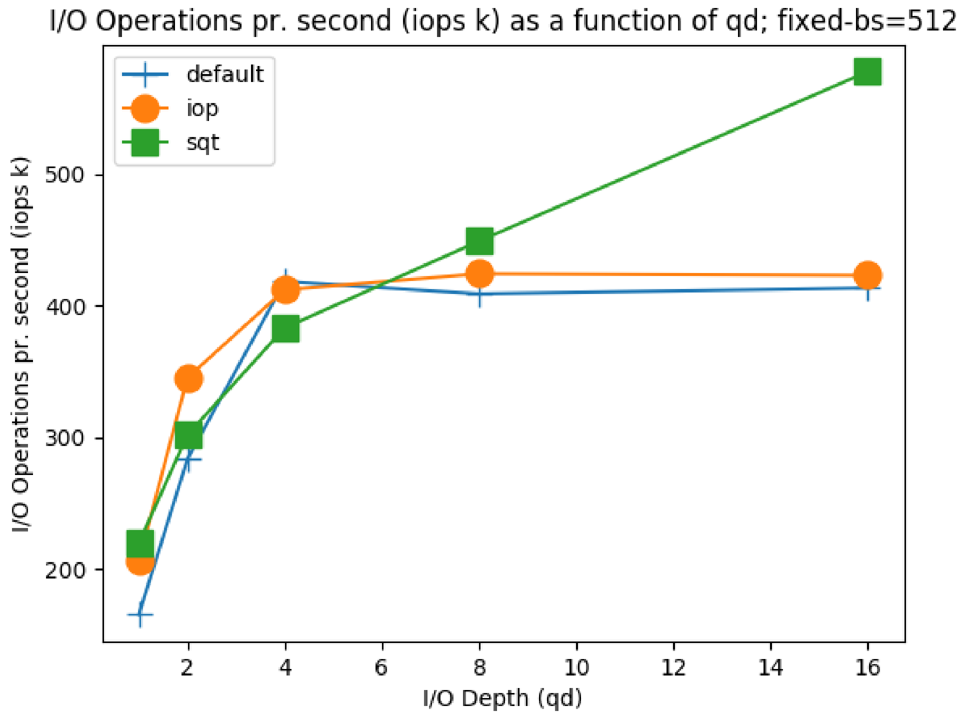
  - Random-read spanning the entire device
- **io_uring** tunables; using submission-queue-thread-polling, register files + buffers, contig-buffer payloads



Performance Evaluation: baseline

- Quantify performance penalty of xNVMe
- Establish a baseline by running without a device
- Fio random-read at qd=1, bs=4k
  - built-in I/O engine **NULL**
  - xNVMe I/O engine using **–async=nil**

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engine \ latency (nsec)	Avg.	Min.	Max.	Std. dev.
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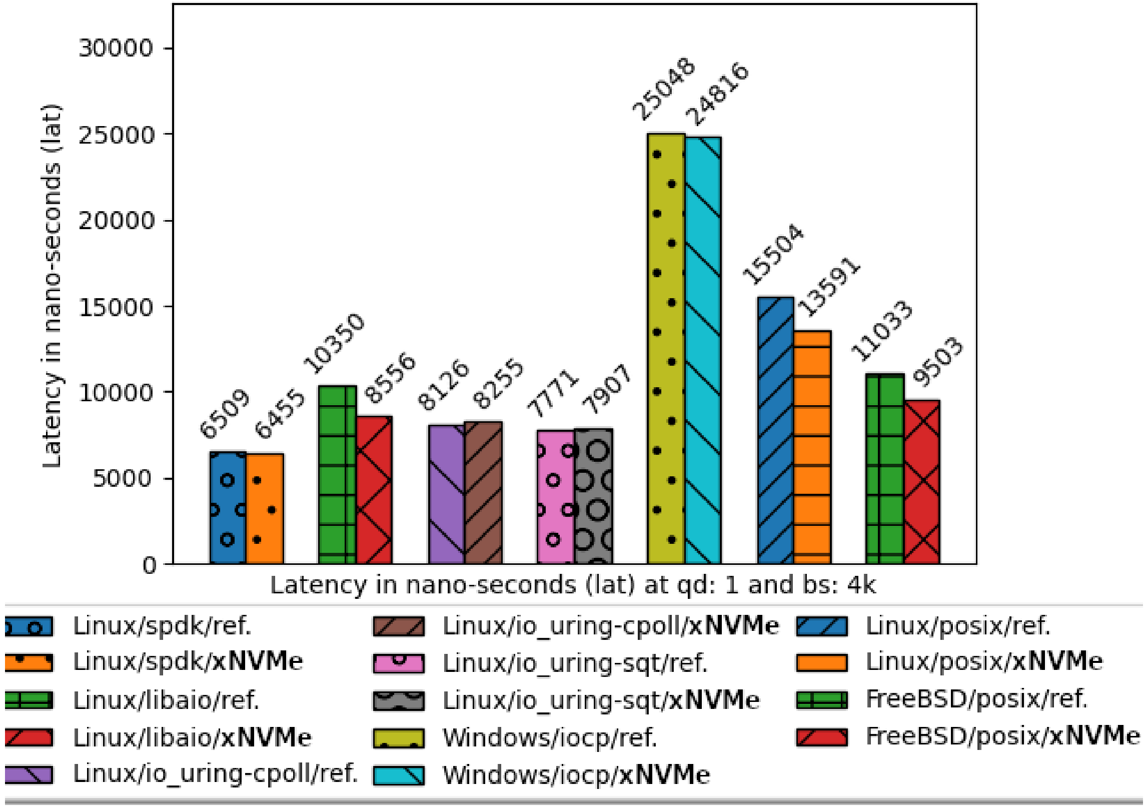
- We will now explore how xNVMe behaves when accessing an SSD through the following I/O interfaces: POSIX aio (FreeBSD + Linux), libaio, IOCP, io_uring and SPDK/NVMe.

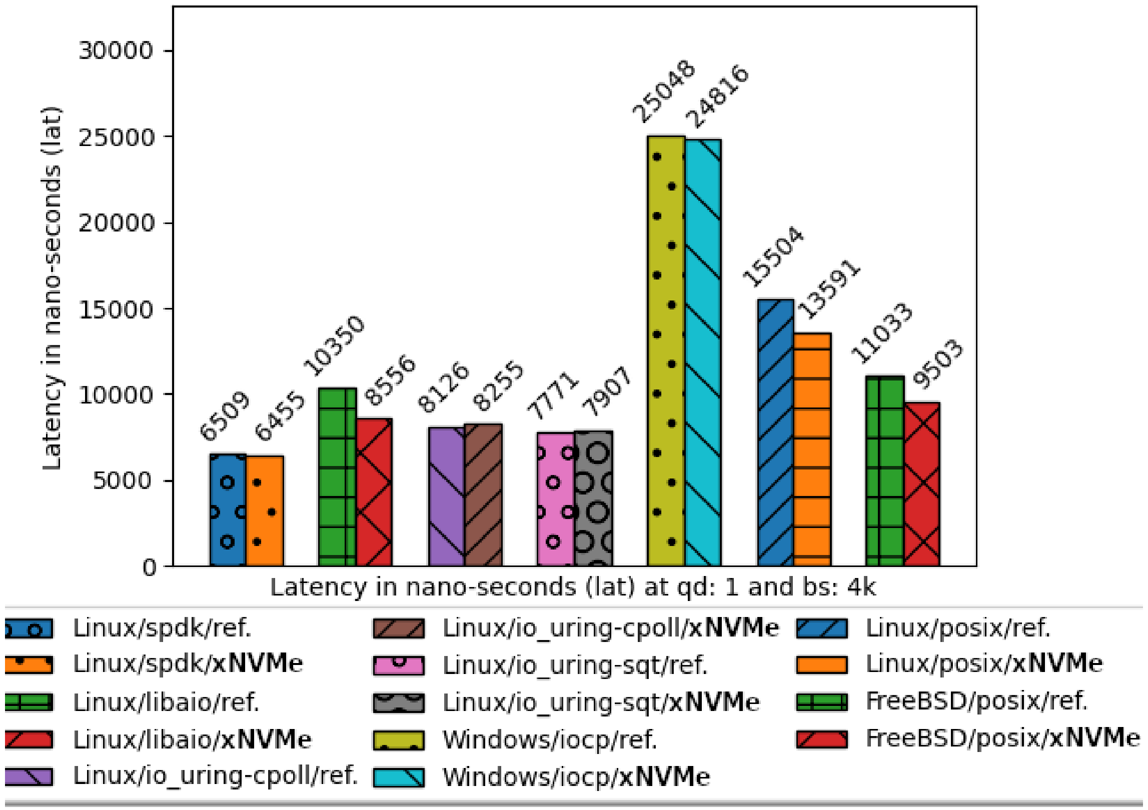
Performance Evaluation: interface qd=1, bs=4k

- Quantify performance penalty of xNVMe
- **expected** penalty = reference latency + baseline + I/O specific



Performance Evaluation: interface qd=1, bs=4k

- Quantify performance penalty of xNVMe
- **expected** penalty = reference latency + baseline + I/O specific
- Expectation is met for io_uring
  - Penalty = ~**136 nsec**



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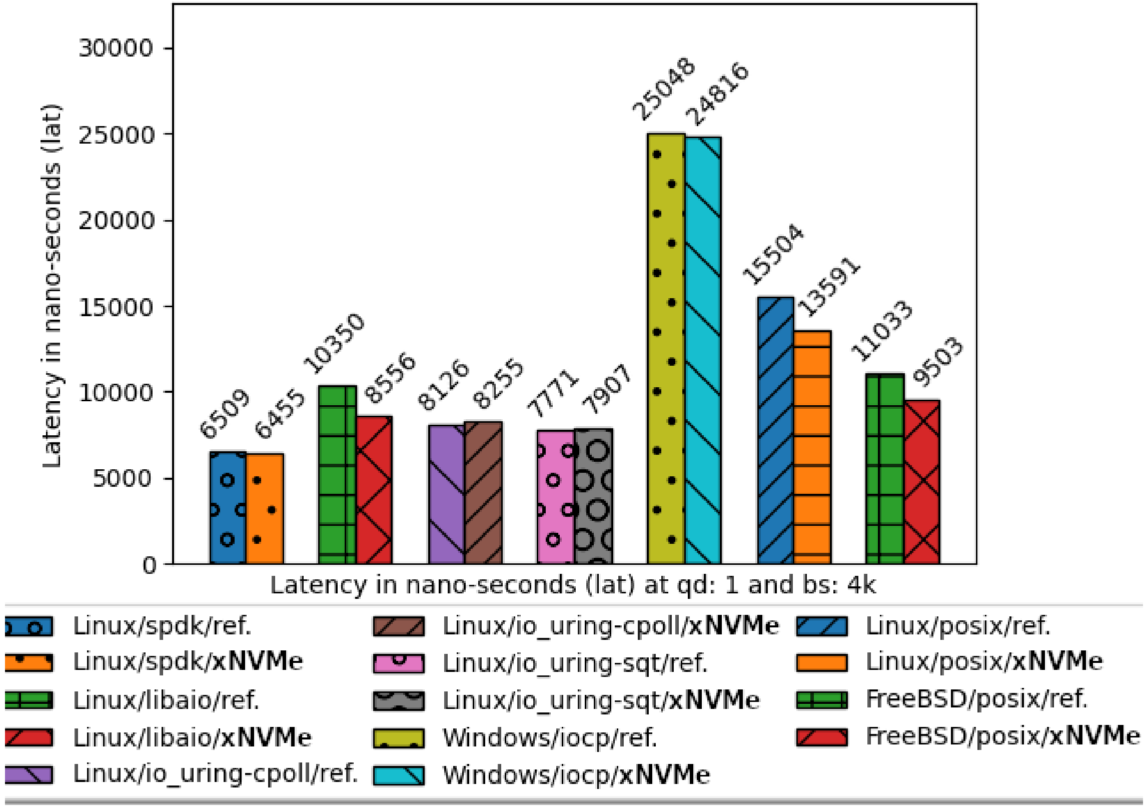

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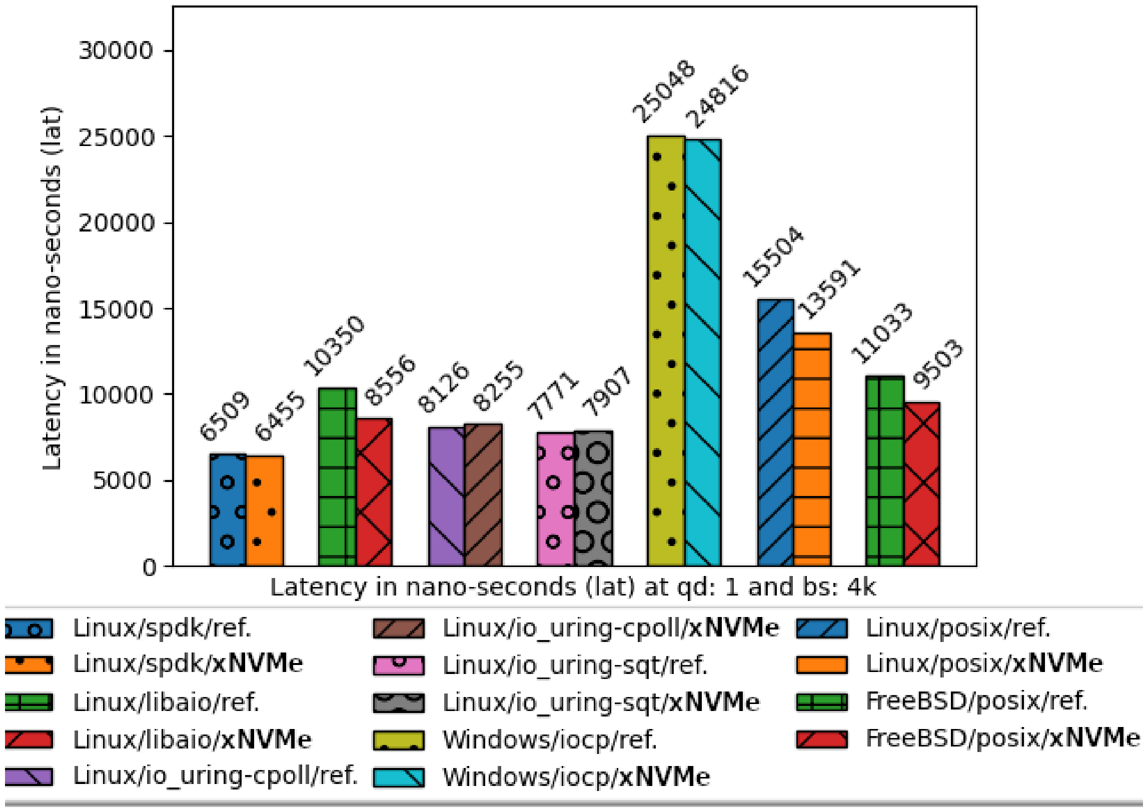
- **expected** penalty = reference latency + baseline + I/O specific
- Expectation is met for io_uring
  - Penalty = ~**136 nsec**
- Otherwise, same/less ➔ Why?
- Interrupt-driven I/O interfaces
  - xNVMe spins instead of waiting for interrupt/wakup
- SPDK/NVMe
  - Different IO engine, doing more work
  - Hooks in at a higher-level in the driver



Performance Evaluation: scalability check

- Varying **queue-depth** (qd)=[1,2,4,8]; fixed block-size (bs)=4k
- Varying **block-size** (bs)=[512,4k,32k]; fixed queue-depth (qd) =1

- The above visualized as plots of latency as a function of the varied parameter

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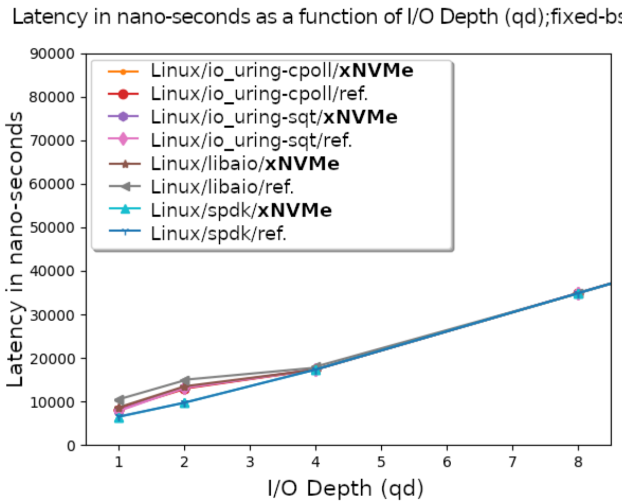
- Varying **block-size** (bs)=[512,4k,32k]; fixed queue-depth (qd) =1

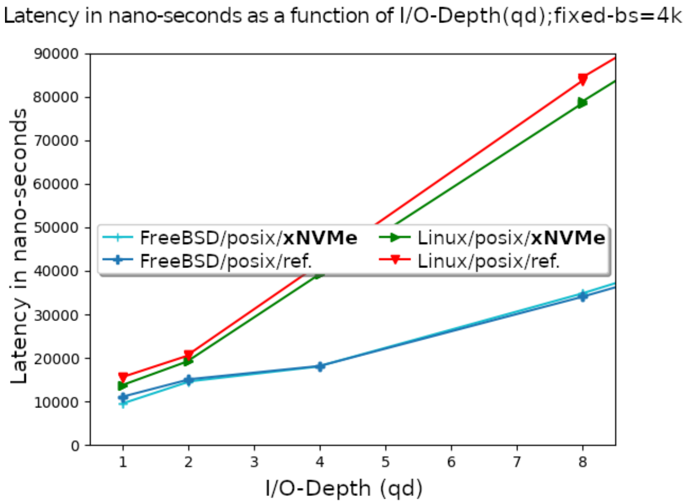
- The above visualized as plots of latency as a function of the varied parameter

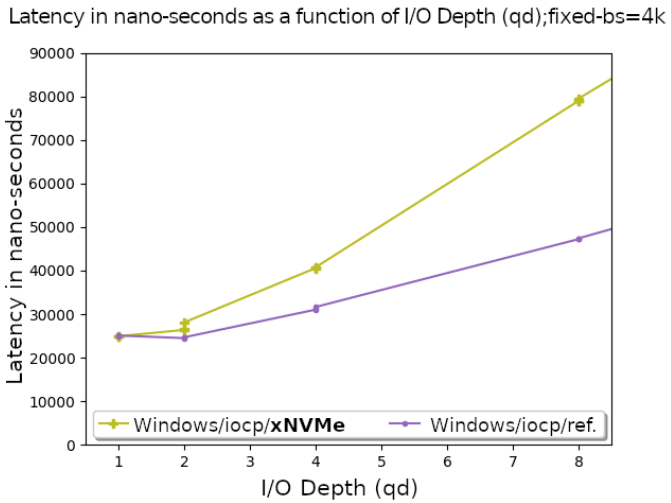
- A **perfect** result would illustrate xNVMe and the reference implementation as lines parallel to each other
  ➔Thus, the xNVMe overhead does not degrade with increasing queue depth or block size

Performance Evaluation: scalability check

- Varying **queue-depth** (qd)=[1,2,4,8]; fixed block-size (bs)=4k







- A near **perfect** result is achieved on all accounts for the xNVMe implementations, except for the Windows I/O interface, this has been identified as a short-coming in the backend implementation

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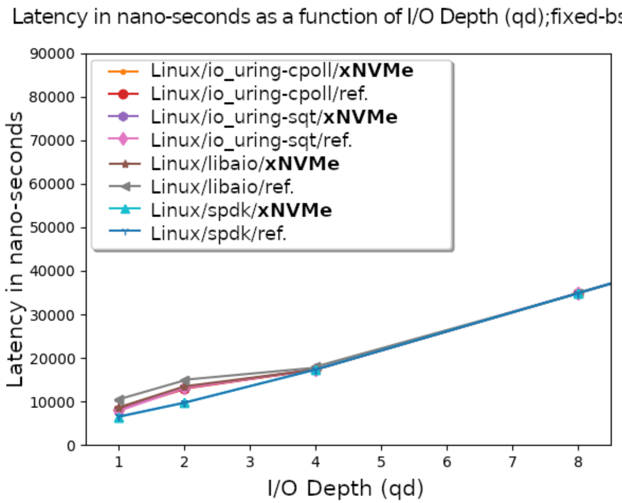
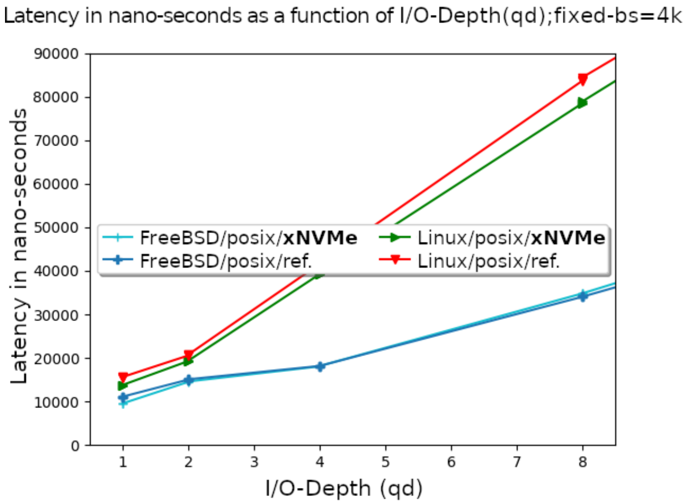
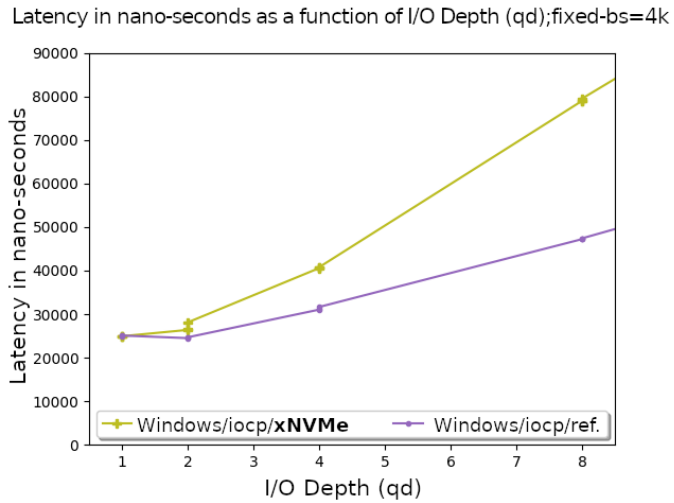


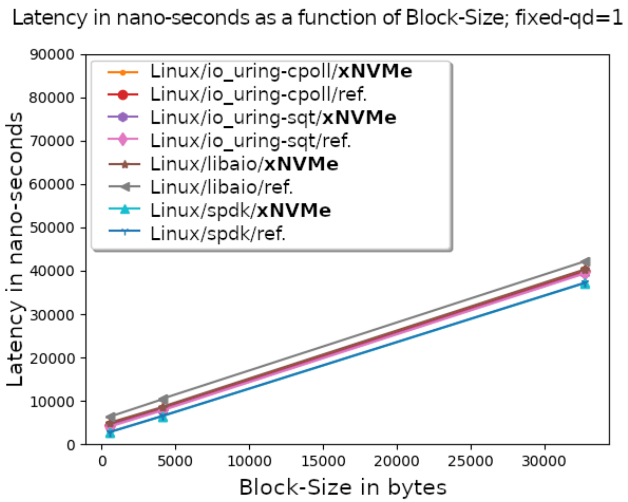


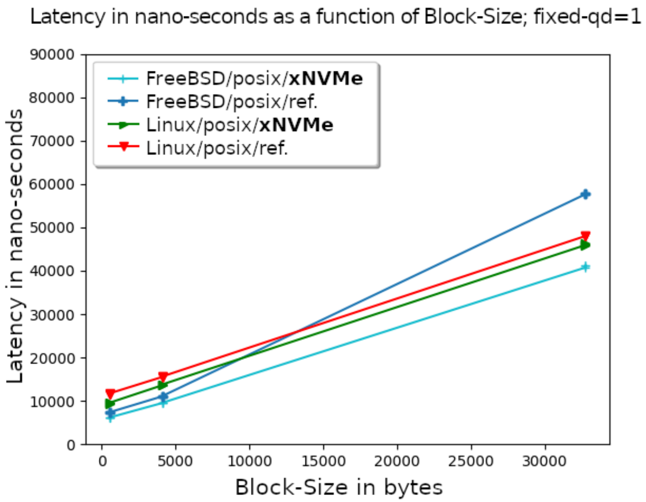


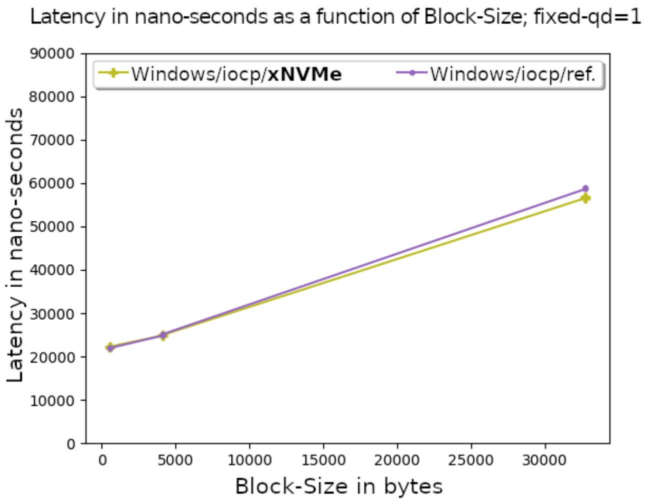
- A near **perfect** result is achieved on all accounts for the xNVMe implementations, except for the Windows I/O interface, this has been identified as a short-coming in the backend implementation
- Observations **unrelated** to xNVMe:
  - POSIX aio does dramatically better on FreeBSD than on it does on Linux.
  - On Linux, io_uring, libaio and SPDK saturates the device at QD4.

Performance Evaluation: scalability check

- Varying **block-size** (bs)=[512,4k,32k]; fixed queue-depth (qd) =1







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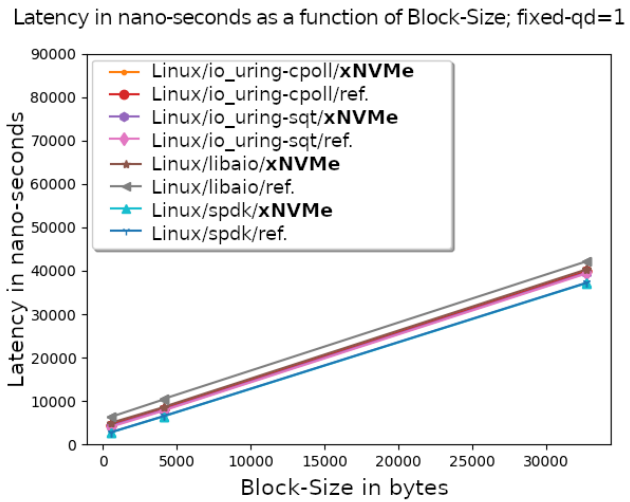
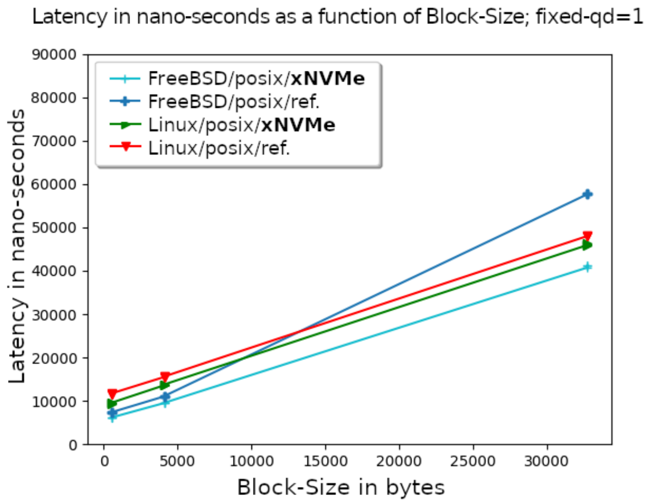
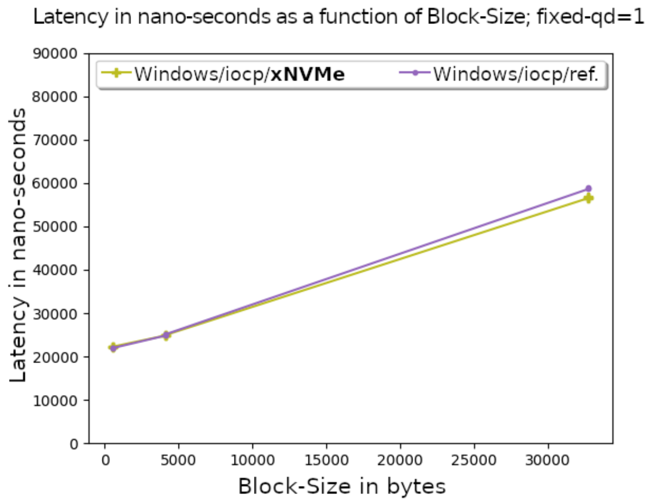






- A near **perfect** result is achieved on all accounts for the xNVMe implementations, and thus the xNVMe penalty is constant in this regard.
- Observations **unrelated** to xNVMe:
  - POSIX aio on FreeBSD has issues with larger block-sizes.

Performance Evaluation: conclusion

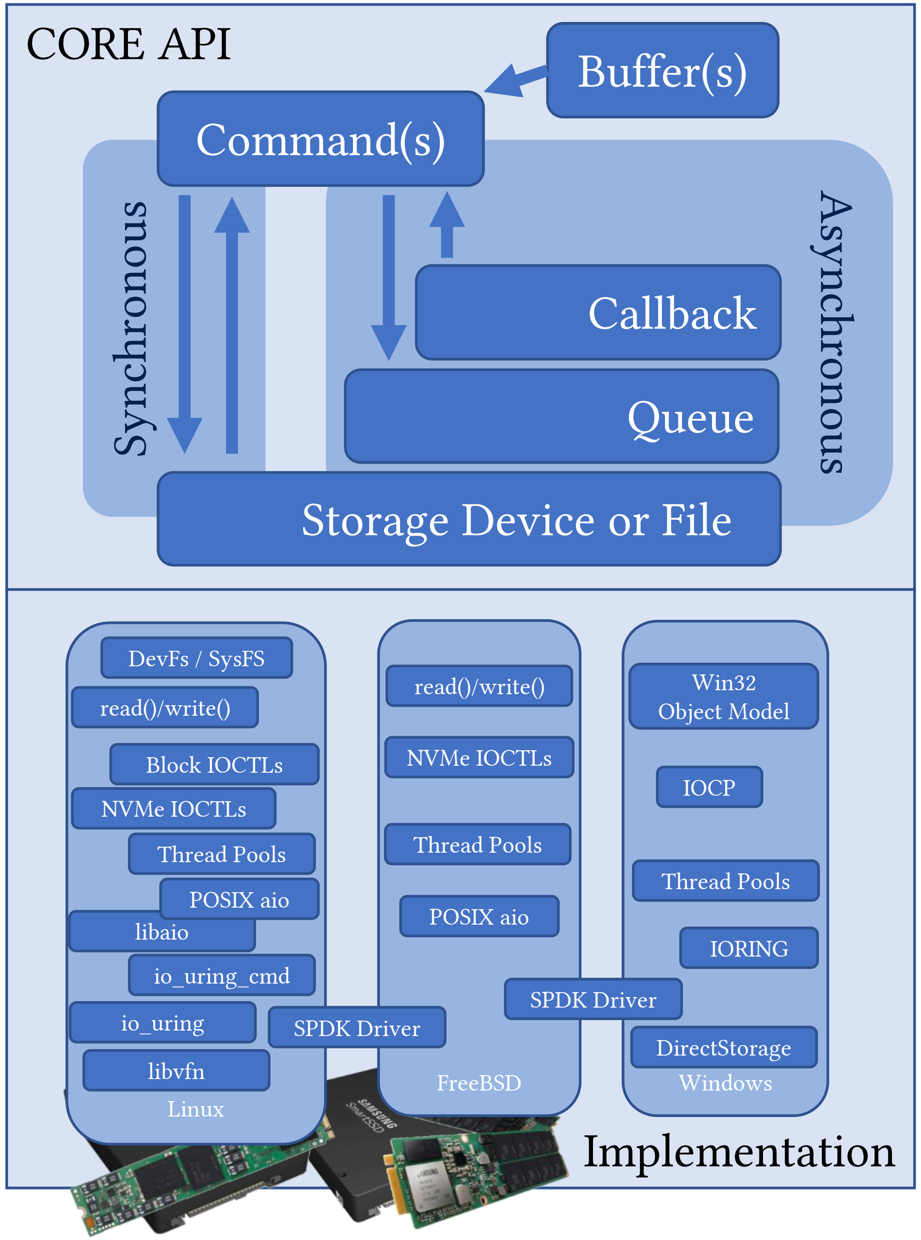
- Quantify performance penalty of xNVMe
- Baseline penalty ~ **54 nsec** per I/O

- io_uring penalty ~ **129 nsec** to**136 nsec**
- Interrupt-driven; **less** than reference due to completion-processing
- User space; **less** due to minor difference io-engine implementation

- The **penalty** is constant when scaling I/O depth and block-size
  - Except for Windows IOCP

Extensibility: a recent example

- Support for Linux async. NVMe Passthru
  - Aka **io_uring_cmd** / async. ioctl()
- Linux Changes
  - Generic namespace char-devices **/dev/ng0n1** (5.15)
  - Extension of **io_uring** big-sqe & big-cqe
  - **NVMe sqe/cqe** embedded in **ring-sqe/cqe**
  - Non-NVM Command-sets ➔ **efficiently** (5.18)
- xNVMe
  - System interface handled by library backend
  - **No changes to CORE API**
  - **No changes to upper-layers**
  - **No changes to the application**



Recent Developments 1/2

- MacOS Support
  - Basic usability of psync, emu, and thrpool
  - Targeted for **v0.5.0**

- libvfn backend
  - Linux vfio-based user space NVMe driver for low-level tinkering
  - See: https://github.com/OpenMPDK/libvfn
  - Targeted for xNVMe **v0.5.0**
- Python Bindings
  - **ctypes** and **Cython**
  - Targeted for xNVMe **v0.5.0**

Recent Developments 2/2

- **Fio**
  - xNVMe is merged in upstream **fio**
  - Available upon release of fio **3.31**

- **SPDK**
  - bdev/xNVMe patchset in-review, has 2x **+1** from reviewers
  - Targeting SPDK release **22.10**

Summary

- I/O Interface Independence is achievable with **xNVMe** for a cost of **54** to **136 nsec** per I/O

- Unified API for the continuing innovation on I/O interfaces
- **Fio**, available **now** in upstream **master**, released with fio **v3.31**
- **SPDK** bdev-integration targeted for SPDK **v22.10**

- Documentation: https://xnvme.io/docs/
- Repository: https://github.com/OpenMPDK/xNVMe
- SYSTOR22 Article: https://dl.acm.org/doi/10.1145/3534056.3534936