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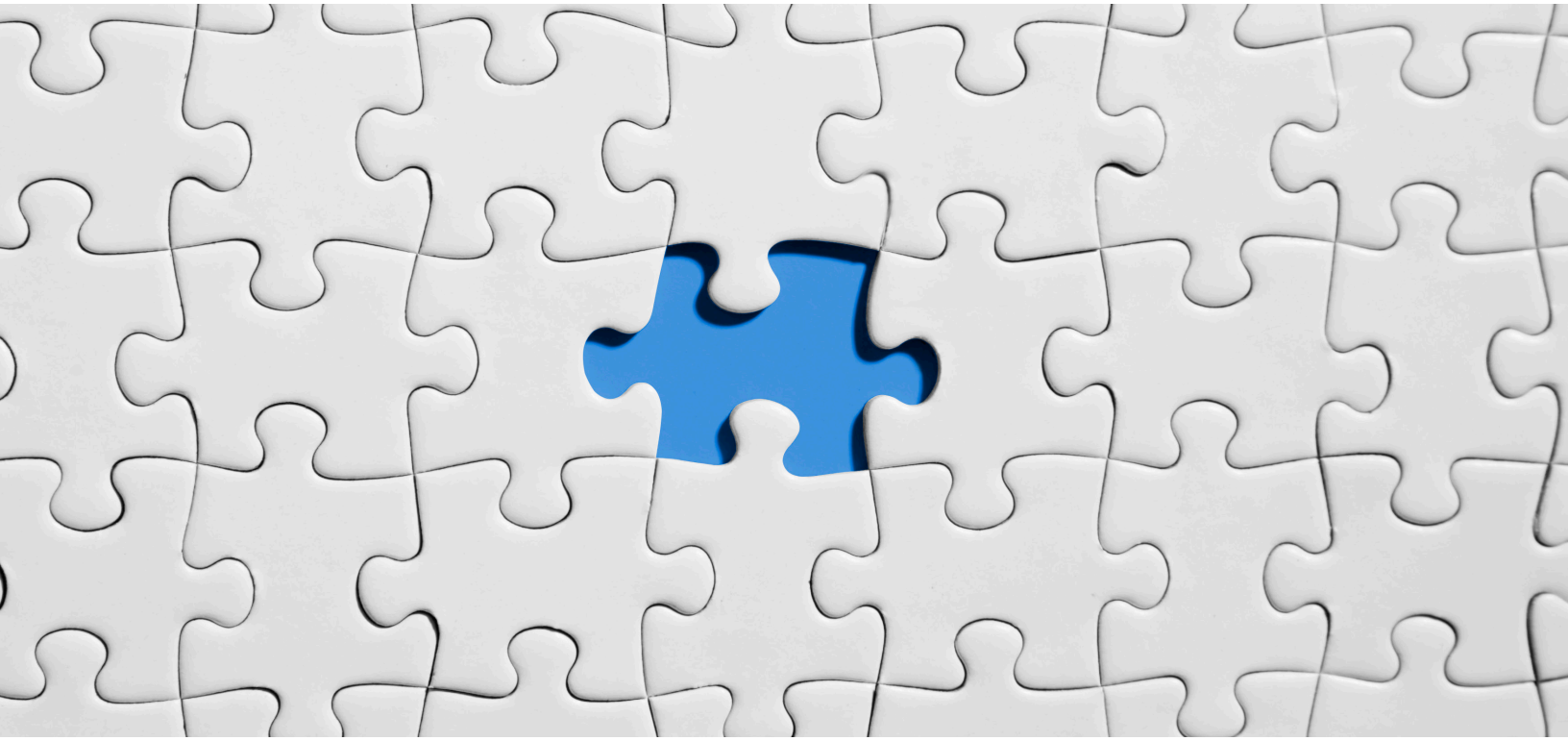
THE EVOLUTION OF ENTERPRISE STORAGE



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Knowledge Sharing Article

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Everything Must Change

Twenty years ago, Windows 98 pulsed through high-end 500MHz Pentium PCs with 64MB of memory and a 10GB hard drive.[1] Companies built three-tier architectures of servers, a gigabit Fibre Channel Storage Area Network (SAN), and a “star-wars” looking EMC Symmetrix 8430 machine with dozens of 36GB Small Computer System Interface (SCSI) hard drives. The 32GB cache array maxed out at 3½TB of storage and allowed access to data in cache or a much slower hard drive layer. Storage engineers designed solutions by adding up workloads and dividing by drive capacity and Input/output Operations Per Second (IOPs), often over-designing them to meet workload peaks. Customers flocked to SANs instead of server-based Direct-Attached Storage (DAS) to increase utilization, reduce costs, and improve manageability and scalability. The enterprise storage world loved it!

A decade later, Windows XP used a 1.7GHz Pentium 4 PC, 80GB drive and 256MB of memory.[2] Companies upgraded their SAN to 4Gb/s and a behemoth 10 ton, 9 rack DMX-4 with 2,400 hard drives for 2PB of storage.[3] A revolutionary hard drive shaped 73GB SCSI Solid-State Drive (SSD) dramatically boosted drive-resident application performance. Each $18,000 SSD, which was comparable in performance to today’s small USB flash drive, lacked the capacity and proved too expensive to replace spinning disks.[4,5]

Today, a Windows 10 PC runs on a 16GB 8-core processor at 3.6GHz with a 1TB SSD. On the SAN-side, data center modernization and transformation can leverage a two rack, 4PB PowerMax with a streamlined massively parallel protocol and interconnect for Storage Class Memory (SCM) and Non-Volatile Memory Express (NVMe) SSDs. Engineers now leverage platforms with 50% more performance than the previous generation and trim costs by sizing solutions based on effective deduplication rates. IOP performance and workload peaks are automatically handled.[6,7] Can we possibly process data any faster?

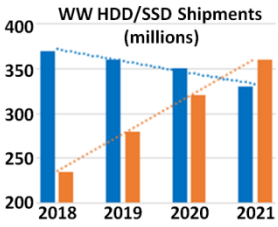
While SANs are still popular, the twenty-year-old movement that freed storage from servers is starting to come full circle. Virtualized multicore processors with fast interconnects have led some customers to innovative x86 Hyperconverged Infrastructures (HCI) and Software-Defined Storage (SDS) rather than older three-tier architectures. SAN features of file, block, and object protocols, clones and snapshots, encryption, compression/deduplication, and replication are no longer exclusive. SDS storage architecture can lower operational and capital expenses that

challenge today's IT budgets. These new solutions incorporate SSDs in all sorts of packaging to revolutionize enterprise storage designs.

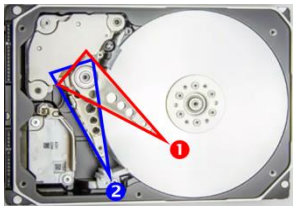
Our innovative world is full of change. From a technology perspective, while hard drives, mainframes, and magnetic tapes are still in use, the pace of change has increased. Similar capacity and performance of a high-end circa 2000 Symmetrix can be found in an enterprise server at a fraction of the cost. Just 6 layers of a 96-layer NOT AND (NAND) logic gate chip can hold the contents of a large 10TB hard drive.[8] (NAND chips are SSD building blocks and covered in detail later on.)

Computer storage is on the precipice of yet another shift. Moore's Law is being kept alive with new types of storage that doubles the performance while halving the cost. The enterprise storage world is constantly evolving and this paper is about those elements of change.

Hard Drives Losing Ground to Solid-State Drives



The annual hard drive unit growth rate is in decline. Worldwide **hard drive** shipments slipped 2.5% annually from a 370 million unit peak in 2018 to 330 million in 2021. Meanwhile, **SSD** shipments increased 13% annually to 360 million units.[9] High performing 15K RPM **hard drives** hold 900GB while large capacity 20TB **hard drives** run at 7,200 RPM, both smaller and slower than large high-performance **SSDs**.[10,11] Systems needing fast response and high transfer rates now use SSDs instead of 10K-15K RPM drives while applications such as video surveillance still use lower-performing, lower cost 5,400-7,200 RPM units.[12] While the market for older hard drive technology is shrinking, 240 exabytes of rotating platters shipped in Q3 2019.



A decade ago, some programs that used four hard drives for capacity now use one high density, high throughput dual actuator Heat Assisted Magnetic Recording (HAMR) 20TB drive as shown to the right. Two active heads double the IOPS and performance to 480MB/s for less critical applications and high-performance secondary workloads. Seagate is planning a new 100TB HAMR drive for 2025.[13,14]

Just two decades ago, a $500,000 storage rack held a few terabytes of data. Concurrent access was limited to a handful of small SCSI hard drives while consuming many kilowatts of power and dissipating thousands of BTUs of heat. SSD innovations such as Triple-Level Cell (TLC) with a 128-layer 1Tb die (a rectangular integrated circuit sliced from a circular wafer) are happening faster than hard drive improvements. Breakthroughs with lower cost 144-layer Quad-

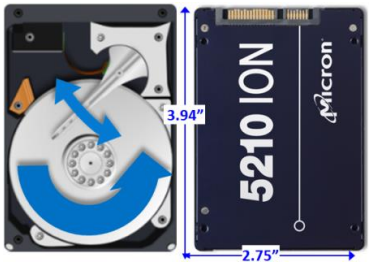
Level Cell (QLC) 2½" SSDs and future 176-layer QLC SSDs could yield a 120TB hard drive form factor.[15,16] Without a rotating platter, SSDs can take on different shapes, allowing thirty-two 170TB SSDs with a new shape to deliver 5PB of storage in a 1U server or 217PB in a full rack. This density/performance improvement helps close the SSD/hard drive price gap.

Motorized hard drives limit performance. I/O commands queued against fragmented data experience higher latency due to increased head movement and rotational delay, resulting in fewer IOPS and lower throughput. Latency, similar to the occasional lag between a TV video and voice, critically represents the delay in programs getting I/O responses. Amazon equates 100ms of latency with a 1% web sale loss.[17] SSDs do not have mechanical issues and easily handle parallel low latency commands, making them ideal replacements for aging hard drives.

Lastly, hard drives seem to fail at a higher rate than their counterparts, although it is worth noting that SSDs also wear out as we will discuss. The idea of critical components wearing out is not new; after all, our cars have a spare tire for a reason.

New Shapes

It helped early SSD product adoption to use the familiar 2½" rectangular hard drive shape and fit into existing drive slots. They used the same interface such as SCSI (introduced in 1981), Serial Advanced Technology Attachment (SATA), Serial Attached SCSI (SAS), and Peripheral Component Interconnect Express (PCIe).[18] This illustration shows the shape of a 2½" QLC SSD is identical to a SCSI hard drive.



A U.2 drive represents the next phase of hot-swappable SSDs using a hard drive shape. It uses the same SAS/SATA connector although the pinouts carry different signals[19]. Whereas the SAS/SATA connector maps to a drive controller which then interfaces with PCIe, U.2 drives do not require a controller and use the connector to map directly to a PCIe connection.

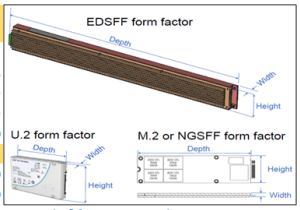
M.2 SSD cards were originally called Next Generation Form Factor (NGFF). The M.2 2280 (22mm x 80mm) is the size of a pack of chewing gum. Unlike 2½" enterprise SSDs, M.2 is not "hot" replaceable. They require the computer to be turned off since they plug into a dedicated motherboard slot (or PCIe adapter card) and are not inserted from the front of the machine. The cards scale up to 2TB of capacity and lack a protective case. With the same general SSD circuitry but in a narrow form factor, they are available with a SATA or a four-fold faster NVMe interface.[20]

New SSD shapes allow for smaller and more powerful servers by packing more NAND die onto circuit boards for denser capacity. With improved power efficiency and thermal profile, they lower the effective cost per gigabyte and allow for new architectures. One radically disruptive shape is called **E**nterprise & **D**atacenter **S**torage **F**orm **F**actors (EDSFF) or "ruler" for short.

Storage rulers come in a short (**EDSFF E1.S**) and long size (**EDSFF E1.L**). **Short rulers** resemble M.2 drives and plug into the front of a server and support hot-swapping. Just 32 **long rulers** with dense QLC NAND give a server almost a petabyte of SSD storage in just one rack unit (1RU) as shown to the right.[21]

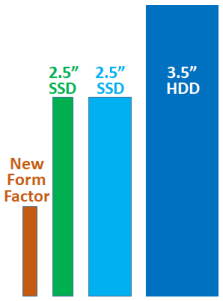
New SSD Form Factor	Height mm	Width mm	Depth mm
EDSFF 1U Short	31.5	5.9/8.0	111.5
EDSFF 1U Long	38.4	9.5/18	318.8
EDSFF 3" Short	76	7.5/16.8	104.9
EDSFF 3" Long	76	7.5/16.8	142.9
NGSFF NF1 M.3	30.5	4.3/4.8	110
Existing SSD Form Factor			
U.2 2.5"	70	7/15	100
M.2	22	4.2	110

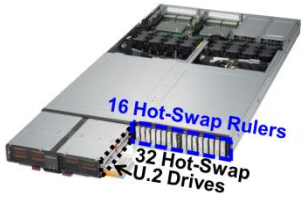
https://www.youtube.com/watch?v=ds588L2Kcdw&feature=youtu.be



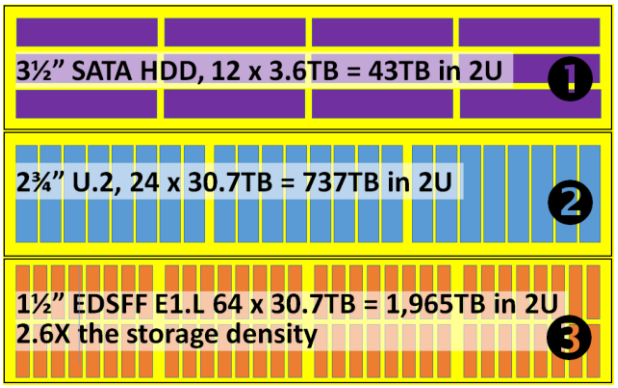
These designs are a clear change in data center removable storage versus the airflow and circuit board size limits of 2½" SATA, SAS, and U.2 drive form factors.

The illustration on the right shows the height and width of these new **ruler** SSDs versus **2½" thin**, **2½" regular SSDs**, and large capacity **3½" hard drives**. Some 1U servers accommodate a mix of rulers and U.2 drives by housing them in swappable independent sleds as shown to the left. Using **32 hot-swap U.2 NVMe drives in a removable deep modular enclosure** and **16 hot-swap storage rulers** in a removable modular enclosure, the server provides 1PB of storage space.





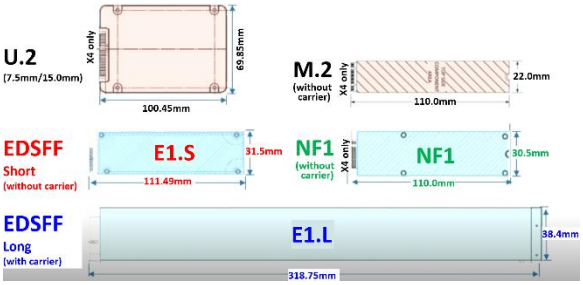
In this scaled drawing, **24 U.2 SSDs**❷ (0.7PB) fit in 2U of rack space while **64 EDSFF rulers**❸ (~2PB or 2.6X denser) fits into the same space. If you compare the **ruler** to **12 x 4TB 3½" hard drives**❶ in **2U**, the ruler is 46X denser. A full **42U rack of hard drives holds 903TB** while a **rack of rulers** is about **41 petabytes**, or conversely, the entire rack capacity of **3½" hard drives** could be reduced to a **single 1U of rulers**. Compared to 2-millisecond latency for a **15K hard drive**, any **EDSFF** can READ 3,200 MB/s and WRITE 1,600 MB/s in 135 microseconds.[22]



Four additional form factors were designed by the EDSFF Working Group. The EDSFF E3 comes in a long 3½" and a short 2½" drive depth in either a 7.5mm (about laptop drive size) or 16.8mm thickness.[23] These 2U shapes will hold about 48 NAND chips or roughly 50% more than a comparable U.2 drive.

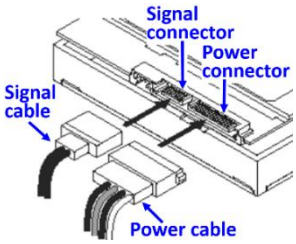
Samsung's **NF1**, originally called Next Generation Small Form Factor (NGSFF), is ⅓ wider and longer than an **M.2 2280** (**22mm x 80mm**) or about the size of an M.2 30110. It's larger circuit board holds 16 dies or 16TB of NAND.[24] Sometimes referred to as an **M.3**, it quadruples the **M.2** capacity, provides hot-plug front-bay serviceability, LED status lights, and uses SATA, SAS or PCIe interfaces.[25] Its dual-ported design adds high-availability for controller redundancy or dual-controller concurrent drive access. The PM983 **NF1** holds 15.36TB and is a fraction narrower than EDSFF allowing 36 of them to provide a 1U server with 550TB of capacity.

This diagram depicts the relative size of the 4.4" (111mm) **E1.S**, the 4.3" (110mm) **NF1**, and Intel's DC P4500 12½" (318mm) **E1.L** QLC ruler that fits into a 1U server. The **E1.S** and **NF1** have the depth of a 2½" drive and six **E1.S** drives fit in the space of two 2½" drives. With hard drives becoming less popular, new form factors such as the ruler shape will allow for greater density.



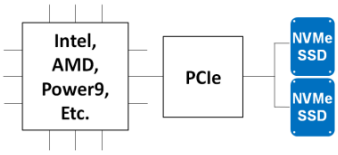
New Interfaces

The twenty-year-old 8430 leverages SCSI hard drive technology from the mid-1980s. In 2003 SATA began replacing the Parallel Advanced Technology Attachment (PATA) found in PCs of the day and soon evolved into an enterprise standard. SATA supported "hot-swappable" replacement of failed drives, provided fast I/O transfer rates, command queuing, and used small lower-cost cables (shown to the right). [26] SCSI Ultra-3 was popular in 2000 and had speeds of 160MB/s while supporting 15 drives per controller port. SATA eclipsed PATA and SCSI with 187.5 MB/s (1.5Gb/s) per drive loop and reached 6Gb/s (750MB/s) by 2009.[27] SATA transfers data in half-duplex (one point-to-point link direction at a time). With SATA SSDs, half-duplex became a processor bottleneck. There are no plans for a faster SATA interface.[28]

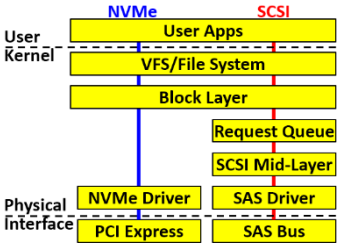


In 2004, SAS doubled the SATA bandwidth and maintained support for hard drives. Today, the 12Gb/s SAS-3 interface is still backward compatible with older SAS and SATA drives. SAS allows 256 queued commands and supports up to 65,535 dual-ported drives. IDC predicts 70% of enterprise hard and solid-state drives sold through 2022 will be SAS or SATA.[29] Unlike half-duplex SATA, full-duplex SAS allows data to be transmitted bi-directionally.

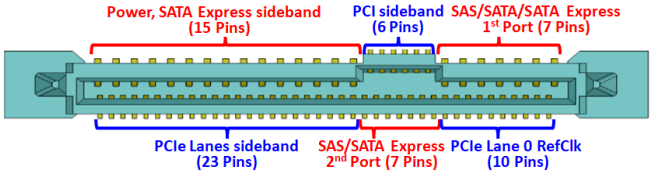
In 2003, PCIe was introduced as a high-speed motherboard slot interface that accepts a graphic card, storage controllers, and other adapters. The latest version has 128GB/s (1,024Gb/s) of bandwidth. The open device NVMe is a key efficient design element in a new SSD interface that also runs on PCIe. NVMe improves application response time, increases bandwidth to dramatically boost SSD performance, and reduces latency, which is the time a CPU wastes waiting for data. Just as SATA and SAS SSDs replaced hard drives in mission-critical enterprise applications, NVMe SSDs will make deep inroads into replacing legacy SSDs. Non-Volatile Memory devices attach to the PCI Express bus and communicate directly with the CPU, so they do not need dedicated storage bus controllers – hence the "NVMe" nomenclature.



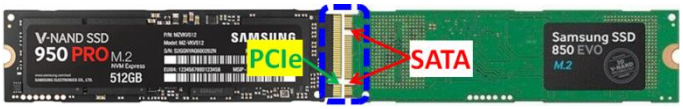
In the past, making an application run faster often meant a processor upgrade. Moving storage electrically closer to the CPU and simplifying the process stack achieves the same goal through increased CPU utilization. This is measured through lower latency, increased throughput, and faster user response time. As this Linux storage stack illustration shows, **NVMe** is much simpler than the hard disk-era **SCSI** stack used in the SAS/SATA interface, allowing **NVMe** SSDs to be much faster than their counterparts.[30]



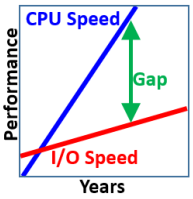
NVMe is not a physical connector so it supports various form factors including a traditional 2½" rectangular shape. U.2 **NVMe** SSDs use the same connector but with different pinouts - the **PCIe in blue** and the **SAS** and **SATA in red**. Internally, a **PCIe NVMe** SSD can be an M.2, fit into a standard **PCIe** motherboard slot, or used as a "ruler."



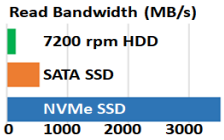
A **double notch** M.2 connector on the right side of this image indicates it is **SATA** and transfers data at **6Gb/s** while **one notch** means it is **PCIe NVMe** and performs up to **three times the speed** of its **SATA** counterpart.



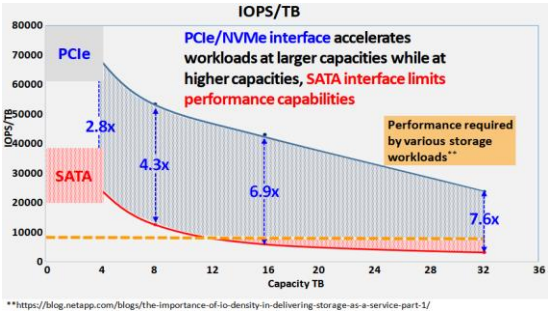
The current SATA and SAS architecture is almost a decade old. Conceived before SSDs came to market and originally supporting hard drives, the combination of design and throughput keeps them from delivering the full potential of today's SSDs. **Processor performance** doubles every two years and is impacted by relatively slow **I/O performance** - the **gap** is increasing. SSDs made great inroads in closing that gap, but it wasn't enough.



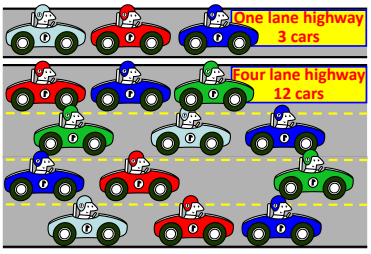
One SSD can transfer 550-4,000 megabytes of data a second and a modern interface allows them to work in parallel on a queued list of I/O commands. With **SATA-3's** maximum **550-600 MB/s** transfer rate, a single SSD with enough commands can be slowed by its interface. **SAS-3** is twice the speed of **SATA-3**, and while its story is better, it too runs into saturation issues that hamper performance. The bottleneck gets worse when a bunch of SSDs on a single loop work on queued I/O commands.



When storage components perform suboptimally, the CPU waits for I/O. There simply is not enough bandwidth from their disk-era design to get the job done. **SATA-3** and **SAS-3** SSDs are forced to perform slower than 4,000MB/s **NVMe** devices even though they generally employ the same NAND chips.



SSD nomenclature such as "**PCIe 3.0 x 4**" describes the older and popular **PCIe version 3.0 interface** with **four serial point-to-point data transfer lanes**. In this illustration, a **PCIe** lane is like a single versus a multi-lane highway where all cars travel at the same speed. The only way to increase highway throughput without speeding up the cars is to add parallel lanes. Devices stripe data across multiple PCIe lanes for increased throughput. A **PCIe 3.0 x 4** device supports **4** x 985MB/s or 3.94GB/s in each bus direction for a four-fold data transfer rate to and from an SSD. For more throughput at the same speed, a **PCIe 3.0 x 8** with **eight** 985MB/s lanes is used. Some **NVMe** SSDs transfer 4GB/s in a four-lane design while SAS is limited to 12Gb/s.[31] Processors such as Intel's i7-8700K has 16 **PCIe 3.0** total lanes while AMD's EPYC has 128 **PCIe 4.0** total lanes.[32,33]



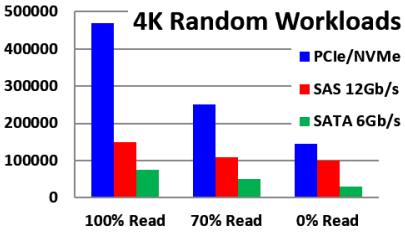
NVMe is a vendor consortium design that permits SSDs to work in parallel with low latency and support thousands of queued requests. It allows the processor to run more virtual hosts and handle more database transactions, thereby increasing core productivity and likely reducing core-based software licensing costs.[34]

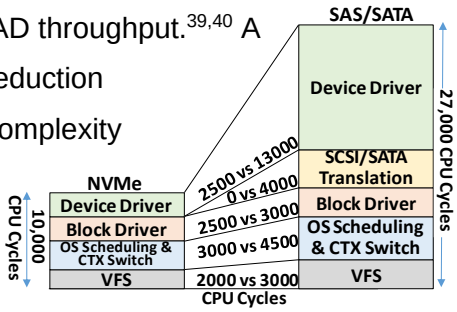
	# Queues	Queue Depth
SATA	1	32
SAS	1	256
NVMe	65,535	65,536

NVMe supports 65,535 queues of 65,536 commands per queue, theoretically handling 4.3 billion commands compared to SAS and SATA's single queue depth of 256 and 32 respectively.[35]

The SAS and SATA single queue approach worked fine for hard drives considering its head movement rotational disk platter delays, but it became an issue when dozens or more SSDs became common in large servers and storage arrays. The highway illustration depicts SAS and SATA single lane local roads restricting the SSD to single queue activity.[36] Today's processors with NVMe accomplish much more work than their predecessors.

SATA uses four non-cacheable CPU register READs per I/O command while NVMe doesn't need them.[37] SCSI's older storage stack is encumbered with a hard drive serial queuing I/O approach that adds 2.5µs of latency when coupled with CPU overhead. A QLC PCIe NVMe SSD (175,000 IOPs) random READ speed is 329 times faster than a SATA 7,200 RPM hard drive (532 IOPs), translating into more processing with less equipment.[38] NVMe offers three times the IOPS of SAS SSDs and twice the sequential READ throughput.[39,40] A 33% NVMe CPU overhead reduction compared to SAS or SATA complexity from the PATA era allows the CPU to work on other tasks, use fewer cores, or consume less power. To the right are some of the SAS/SATA versus NVMe differences[41]:

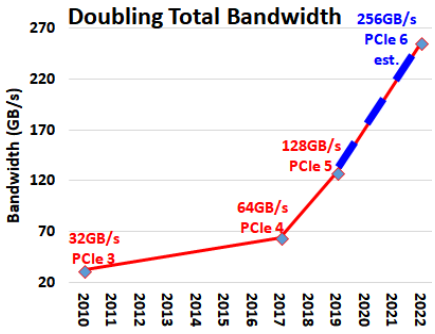




- uses 27,000 CPU cycles to handle 1 million IOPS compared to 10,000 for NVMe
- may need many controllers, each adding overhead
- SCSI translation adds 3µs and 4,000 cycles while NVMe removes this step
- consumes nearly 3x more CPU resources than NVMe

Just like an SSD helps improve system throughput compared to a hard drive, PCIe 3.0 improved the performance of the system bus that supported these SSDs and other adapters. In 2017, PCIe 4.0 doubled the performance allowing a server to support many more NVMe drives.

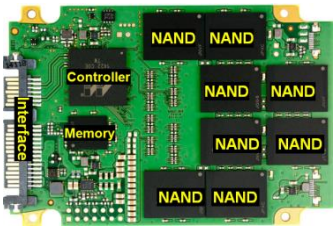
This year, PCIe 5.0-based servers will again double the total bidirectional performance to 128GB/s. PCIe 5.0 quadruples the legacy PCIe 3.0 standard, greatly improving virtualized computing density.[42,43] A single PCIe 5.0 lane at nearly 4GB/s has almost 500 times the data throughput of the original PATA PC interface. Work has begun on the **PCIe 6.0** specification



and in 2022 it should double performance yet again. These improvements allow NVMe devices such as U.2, M.2, and the EDSFF rulers to remove a choke point and support more devices at faster speeds. Lastly, NVMe drives cost about the same as SAS/SATA SSDs.

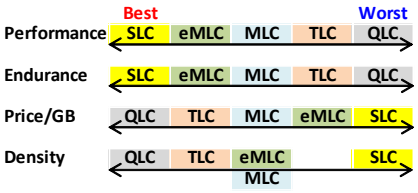
How Do SSDs Work?

At a high level, SSDs follow this generic image. Using a USB, SATA, SAS or PCIe interface, they interact with a controller, memory/cache, and one or more NAND chips on parallel channels. Some SSDs physically combine functions like the controller and memory. And as mentioned earlier, they come in different form factors.



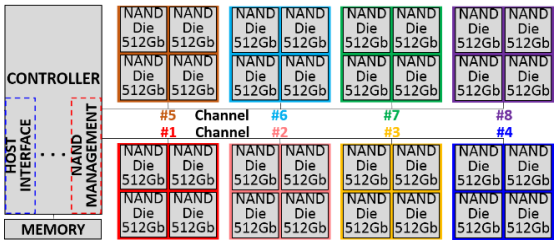
The controller is critical to coordinating incoming host data requests, using memory to maintain data placement tables, orchestrate READ/WRITE operations, perform garbage collection, and map out bad cells. It also refreshes each cell's charge to maintain data integrity thresholds since they leak electrons. Without a charge, NAND cells can retain their contents for about 8 years at room temperature or about a month in a very hot car.[44]

The heart of an SSD is the NAND cell, and no one cell type is best for every workload. The NAND variants are:



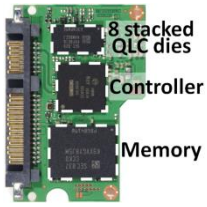
1. **Single-Level Cell (SLC)** – Highest performing. Better WRITE endurance than eMLC. Used in enterprise-grade SSDs. Most expensive which hurts mass adoption.
2. **Enterprise Multi-Level Cell (eMLC)** – Enterprise use. Higher write capability than MLC, but less than SLC. A lower-cost alternative to SLC.
3. **Multi-Level Cell (MLC)** – Used to be mainstream. Slightly slower than SLC, it cost much less to produce. Lower endurance than SLC or eMLC.
4. **Triple-Level Cell (TLC)** – Originally for budget-oriented SSDs. Has lower WRITE/reWRITE endurance than MLC and lower per-GB cost - a strong case for value.
5. **Quad-Level Cell (QLC)** - Latest architecture with 33% more bit density than TLC NAND.

An SSD's circuit board of NAND chips are connected to channels that support multiple independent parallel activities as directed by a multicore controller. A NAND die is measured in gigabits, and in this example each is 512Gb. We have 4 die per channel and 8 channels for a 2TB SSD:[45]



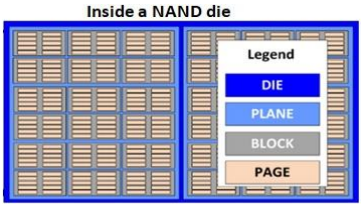
$$4\ dies\ x\ 8\ channels\ x\ 512Gb\ per\ die = \frac{16{,}384Gb}{8\ bits\ per\ byte} = 2{,}048GB = 2TB$$

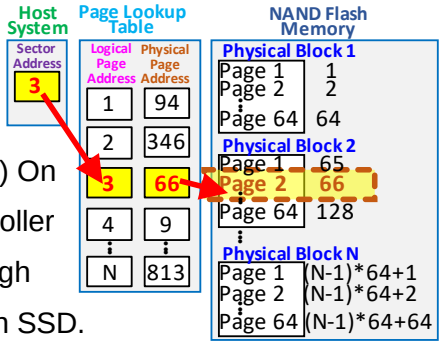
NAND die, controller and memory miniaturization reduce circuit board surface area to keep costs low and improve performance. On the right, Samsung's 1TB QLC SSD needs just three chips for the entire device! The controller accesses 8 stacked QLC chips allowing it to process multiple requests in parallel.



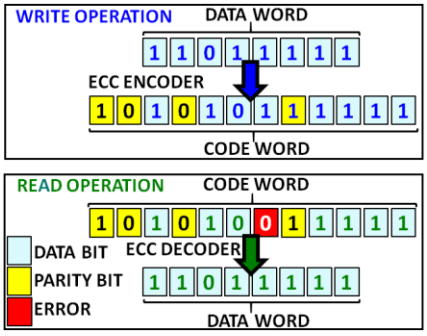
Anatomy of a READ

Like a hard drive, a host sends a command such as a Windows READFILE to the SSD to find specific data. The SSD controller gets the READFILE command and the address of the data from the interface, and translates it into a request based upon the number of die, planes, blocks, and pages on the circuit board (see image to the left). SSDs can have 8 or more die with each having multiple planes. A plane has thousands of 256KB or 512KB blocks with 64 or more pages per block. A page has 32 rows of 32,768 cells representing 4,096 bytes (4KB). READs and WRITEs are at the page level while erasure is on all 64 pages in the block (which explains why erasure takes a while.) On the right, a **Host** issues a READ of **NTFS Sector 3**. The controller sends the contents of **NAND Physical Block 2**, **Page 2** through the SATA interface. The host is unaware the data was from an SSD.





SSD evolution makes the controller's error correction capability critical as NAND chips wear over time, suffer from weak bit signal levels, experience electrical "noise", or have "stuck" bits. Error Correcting Code (ECC) ensures data **written** to NAND chips are reliably **READ** back without error. When ECC struggles to correct errors, the cell is deemed unreliable and a fresh cell takes its place. In this example, the value **11011111** is **written** to the SSD along with extra error parity bits in yellow. With a host **READ** request, an algorithm employs parity correction bits to determine the data stored **11001111** has an error as shown by the **red bit**, and corrects it back to the original string **11011111**.



Unlike hard drive fragmentation, SSD fragmentation occurs as data is deleted or rewritten such as when the Windows recycle bin is emptied (TRIM command) or Word "Saves" a document. NAND chips cannot rewrite in place so discarded data is erased when revised, good data is moved to a new page and the block is erased. Defragmentation housekeeping uses background garbage collection when the SSD is idle or ASAP if space is needed for write activity. Assume

Block A has 6 pages. Page **data4** needs updating and **old data** needs erasing. All **data** pages are copied to new **Block B** and **Block A** is erased to a "free" state. Writing a free block is faster than rewriting data.

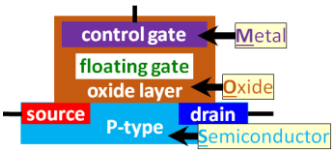
Block A	Block A	Block B
data1	free	data1
data2	free	data2
old data	free	data3
data3	free	update data4
old data	free	free
data4	free	free

A controller experiences write amplification (WA) overhead when it writes more blocks to free up space than the host request. For example, writing 512 bytes to a 4KB page is a WA of 8 ($\frac{4KB}{512\ bytes} = 8$). Excessive writing prematurely wears out an SSD, so it is stored in a buffer until there is a sufficient amount to optimally write out. Garbage collection adds to write amplification.

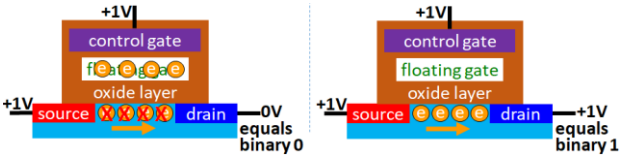
Intelligent arrays tackle WA issues through caching algorithms. "Write folding" replaces similar WRITEs in memory and puts the final one on NAND such as when a program rapidly updates a counter.[46] "Write coalescing" groups small WRITEs into a large one for better page alignment.

What is a Cell?

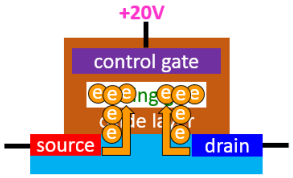
The NAND cell is the heart of an SSD. A cell is a transistor-inspired device called a **Floating Gate Metal-Oxide-Semiconductor** field-effect transistor or FGMOS. An **oxide insulation layer** makes it non-volatile as it traps electrons in the **floating gate**. The lack or presence of **floating gate** electrons represents the binary values 0 and 1. Operations use the **gate**, **source,** and **drain** terminals.



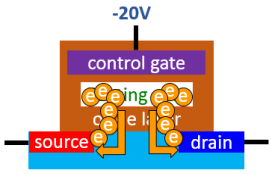
To read from a cell, the controller sends a test voltage to the **control gate** at the cell's address. With SLC, if the **floating gate** has an **electron** charge, that number of **electrons** is <u>prevented</u> from flowing between the **source** and **drain** for a binary 0 as shown to the left. Without a charge, all **electrons** flow between the **source** and **drain** for a 1 as shown on the right.



To WRITE or program the **floating gate**, a high voltage of about **+20 volts** is put on the **control gate**. A quantum physics **Fowler-Nordheim Tunneling** (**FNT**) process causes **electrons** to flow from the **source** and **drain** through the **semiconductor** and **oxide barrier** and land in the **floating gate**. An SLC **floating gate** is a logical 0 with **electrons** and 1 without **electrons**.



ERASING is **FNT** in reverse. When the **control gate** receives **-20 volts**, any built-up **floating gate** charge escapes through the **oxide layer** and out the **source** and **drain**, resetting the **FGMOS** to no charge or 1.

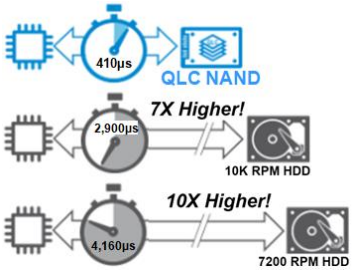


Enter Quadruple-Level Cell SSDs

The mapping interpretation of **floating gate** voltages to logical bits per cell sets the different types of NAND cells apart. In 2006, SSDs used an SLC floating gate that either had a charge or it didn't. In 2009, an MLC stored 2 bits in the floating gate with 3 bit TLC following 7 years later. Each enhancement lowered NAND cost by increasing gigabyte wafer yields which helped drop SSD prices. SLC improvements by-and-large made single-layer silicon planar circuits smaller while today's improvements are focused on increased capacity through multi-cell technologies and three-dimensional multilayer circuits.

A **QLC** FGMOS drain has 16 voltage levels between 0.0 and 1.0 corresponding to values 0000 through 1111 as shown to the right. The same FGMOS is used in an SLC, MLC, TLC or QLC cell, differing only in the binary interpretation of the drain voltage. An SLC drain either has a voltage (programmed) or it doesn't (not programmed) corresponding to a binary 0 or 1. A 2 bit MLC at **.33** volts represents **01** while the same **.33** volts is **0101** in a 4 bit **QLC**. Storing more bits increases the READ, WRITE or ERASE times.

2 bit		4 bit	
Volts	MLC	Volts	QLC
0.00	00	0.00	0000
0.33	**01**	0.07	0001
0.67	10	0.13	0010
1.00	11	0.20	0011
		0.27	0100
		0.33	**0101**
		0.40	0110
		0.47	0111
		⋮	⋮
		0.87	###
		0.94	###
		1.00	###

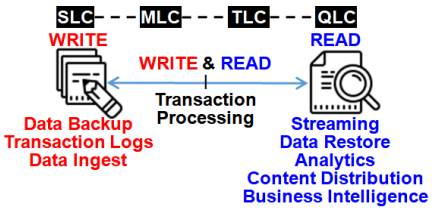


SSDs boost the performance of mission-critical, I/O starved applications. Two years ago, **QLC** SSDs incrementally advanced enterprise storage.[47] SATA **QLCs** are one-for-one plug-compatible replacements for hard drives since they are quiet, use less power, and are faster with a 7-10X latency reduction as shown to the left.

A single SATA QLC SSD, which might use SLC NAND for caching, often replaces many rotating high latency 10K and 7,200 RPM low IOP hard drives just as TLC SSDs replaced 15K hard drives. From an IOP perspective, using QLC SSDs can translate into a reduction of data center racks.[48] QLC has 175 times faster random READ and 30 times faster WRITE performance than hard drives, and use less power and cooling. The popularity and advantages of QLC may force the hard drive market into niche use cases of cold data storage applications as these SSDs become more reliable and affordable.

While many applications do more reading than writing, the downside to QLC is its limited daily write duty cycles, making them suited to READ-intensive environments.[49] To evaluate your environment, review the procedure in the paper "*Understanding Windows Storage IO Access in the Age of SSDs*".[50] Micron's 5210 QLC SSD is rated for 0.8 drive writes per day or 6.4TB/day of writing on an 8TB drive - a hefty amount. This topic will be covered in detail later in this paper.

Workload I/O patterns tend to follow application profiles. QLC SSDs are a good fit for modern applications where data is **written** or **rewritten** infrequently and **read** often such as **content delivery** (e.g. **Netflix**), **video streaming** and other limited-changing data.[51] **Write-intensive** and **data backups, database logs, and ingestion** workloads should be on SLC - TLC. While **machine learning** algorithms feeding artificial intelligence may have 5,000 READs per WRITE, On-Line Transaction Processing (OLTP) is **WRITE**- and **READ**-intensive and best suited for MLC or TLC.[52]

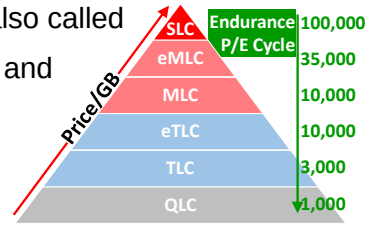


SSD profiles are analyzed with Self-Monitoring, Analysis and Reporting Technology (S.M.A.R.T.) or Windows PerfMon. Micron found a particular server spent 99% of its I/O doing READs – a perfect candidate for QLC SSDs.

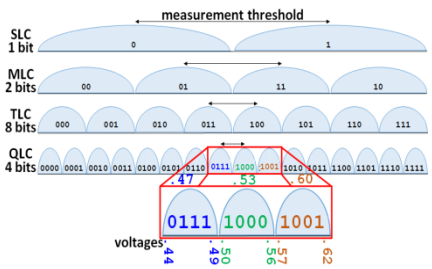
Quad-Level Cells look like an easy concept, but are they?

As discussed, **FNT** is key to **floating gate** electron retention and erasure. However, the high voltage needed to WRITE or ERASE a cell also destroys the **oxide layer's** insulating properties little-by-little every time it is performed. Voltages used to READ are low and do not damage the **tunneling oxide**, but writing and erasing gradually wears out a cell, making voltages inexact.

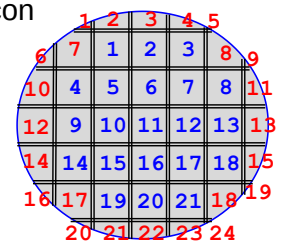
Cell types to the right have different **program/erase** (**P/E**) cycles (also called **wear cycles** or **write cycles**.) Some are more resilient than others and given values are not absolute. Enhanced wear leveling, bad-block remapping/overprovisioning, error correction and write algorithms increase an SSD's life. The SSD controller recovers marginal cell data and restores it to viable cells. An SSD incapable of write activity still provides the data in "read-only" mode. SSDs can take years to wear out and usually become obsolete before reaching **P/E** limits. SLC cells can be written 100,000 times while QLC only 1,000 times. Higher cost enterprise NAND prefaced by "e" have higher **P/E** ratings because of more efficient controller design, giving eMLC a 35,000 **P/E** rating or three times the MLC value.[53]



As cells wear, their drain voltages fluctuate and it is hard to determine their binary value. In this QLC diagram, a controller sends the host **0111** when it reads **.47 volts** from a new cell or between **.44** and **.49** as the oxide wears down. The host receives **1000** for **.50** - **.56** volts and **1001** for **.57** - **.62** volts.



QLC depends on its controller's ECC to ensure stored values are read correctly. If a READ fails, its' block is labeled an unreliable "bad block" and swapped for an "overprovisioned" reserve one. A drive nearing failure has increased ECC overhead causing higher response time. An SSD can have 25% or more reserve blocks based on its warranty.

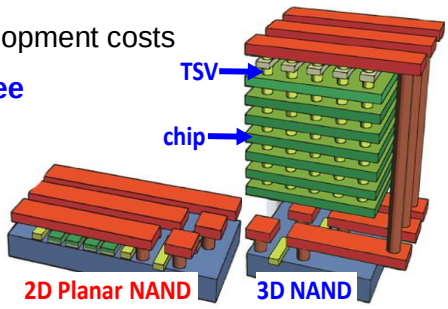


Producing QLC chips is difficult. NAND dies are cut from large etched silicon wafers and a percentage of them fail during testing. Rectangular dies also don't fit well on circular wafers as shown here - **21 fit** while **24** are **incomplete**. Yield equals the number of viable dies after discarding failed or **incomplete** ones. A 300mm wafer yields 148 20mm dies.[54] Currently, the 64-layer TLC's reliable die yield is at 90% while QLC is 48%, meaning only half of the QLC dies can be used in an SSD.[55] High yield levels are necessary for significant price reductions.

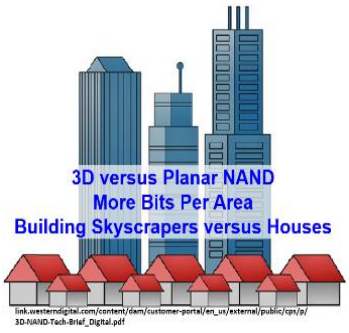
Later this year, Intel and Toshiba plan to introduce 5-bit Penta-Level Cell (PLC) NAND. PLC is expected to support half the write cycles of QLC with a price profile making it compelling to WRITE-once, READ-many applications.[56]

The Big Paradigm Shift – Multi-Level NAND Cells

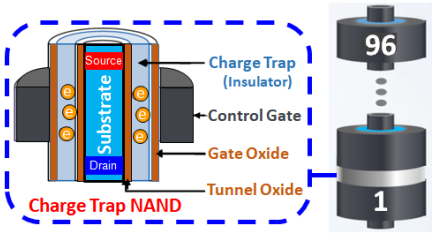
For years, the semiconductor industry followed pioneer Gordon Moore's 1965 prediction that transistor density would double every 24 months. NAND density increased while circuit paths decreased, resulting in lower gigabyte costs. Improvements in photolithography allowed even tinier NAND die. Eventually, makers increased density and lowered costs by building circuits higher rather than increasing surface area – another of Moore's predictions.



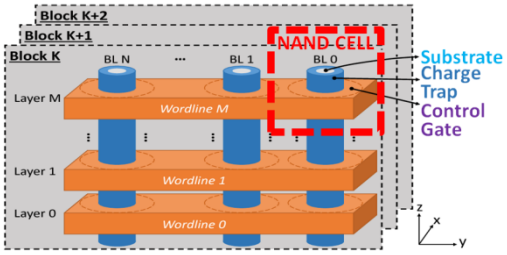
As shown to the right, the storage industry reduced high development costs by moving from **Two Dimensional (2D) Planar NAND** to **Three Dimensional (3D) NAND**. Packing the maximum number of components into the minimum volume is analogous to a high-rise building or skyscraper shape with underground tenant parking instead of 1-2 story houses. **3D NAND** stacks multiple layers interconnected by tiny channels called **Through Silicon Vias (TSV)**. Processing logic is kept in the base and is used to communicate to all NAND layers within the die, all while keeping the same footprint area.



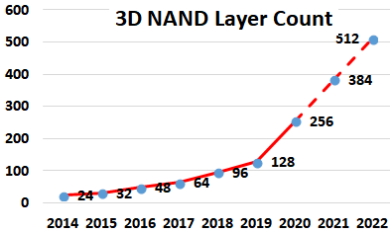
All NAND uses transistors, but some manufacturers reorient **3D NAND** using **charge trap flash** (**CTF**) to lower lithography costs and TSV scaling complexities.[57] In a departure from planar NAND, Samsung's V-NAND boosts cell endurance, minimizes the footprint, and keeps electrons in a non-conductive **silicon nitride (Si_3N_4)** insulating layer rather than in a floating gate conductor. The **control gate** is wrapped around the **CTF**. "Discs" are stacked and the address bitline connects each **charge trap** cell. The **CTF**'s thin insulator uses a lower erase voltage, so cells last longer than classic floating gate cells.[58] The READ/WRITE/ERASE rules are similar.



CTF vertical alignment triples the inter-cell gap reducing the data corruption found in dense planar NAND. Stacked column cells are twice as fast, denser, more energy-efficient, and cheaper to produce than 2D designs.[59] Bitlines run in the block's "Z" axis and span the chip's layers. The insulator covers the bitline and the wordline connects each layer's control gates.[60]



The 1 to 4-bit cell progression and the advent of 64+ layers make storage denser, cheaper per bit, and faster than planar NAND. NAND gigabyte pricing should dip below 10¢ this year or 3X the cost per hard drive gigabyte.[61] Layer counts should reach 256 this year and 512 by 2022 – an 8X increase over 64-layers.[62] Extrapolation shows today's 16TB U.2 SSD will be dwarfed by a 128TB unit in just three years, accelerating the per-gigabyte price decrease. A 1U rack of 32 x 170TB dense rulers should exceed 200PB this year. Contrast that with our 5.4PB 8430 example and we see everything changing.



Endurance Is a Big Question

Hard drive endurance issues stem from their mechanics. A study of 25,000 hard drives showed that nearly one in five fails within four years, and within 6 years, half have failed.[63] Data loss is mitigated through parity, backups, snapshots, data center disaster recovery planning, and other methods.

When SSDs were new to enterprise solutions, storage architects did not have a good feel for I/O profiles and feared WRITE endurance was the device's "Achilles heel". Conservative designs called for drives that could tolerate dozens of Drive Writes Per Day (DWPD). DWPD is the

number of times all SSD data could be rewritten daily and remain in warranty. It usually refers to "sequential" large block versus "random write" small block I/O because of the increased wear caused by write amplification.

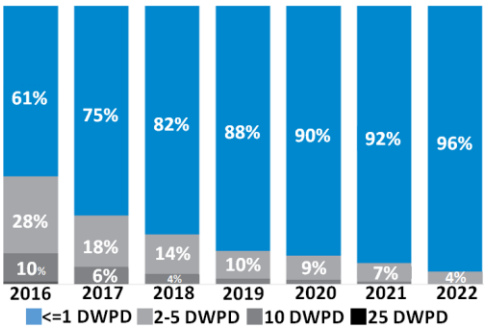
To look at the wear on your Windows 10 SSD, use this PowerShell command:

```
PS C:\> Get-PhysicalDisk | Get-StorageReliabilityCounter | Select Wear
```

The answer returned is a wear percentage. On my PC, I get 6%:

```
Wear
   6
```

As a rule of thumb, a 0.1 DWPD indicates a "READ-intensive" SSD and a higher value such as 10 would be "write-intensive."[64] TeraBytesWritten (TBW) can also help evaluate different SSDs since its numerical value is not tied to the SSD size or warranty. For example, the statement "1 DWPD" for a 1TB SSD means something completely different for an 8TB SSD.



Over time, real-world workload experience allowed for more accurate predictions and selection of optimal SSD technology. This application characterization chart shows the willingness of architects to deploy the right cost-effective technology. In 2006, SLC SSDs with 10 DWPD were popular, but by 2016, 61% of SSDs shipped could handle up to 1 DWPD (a threshold for QLC) and 89% supported up to 5 DWPD.[65] This year, 90% are less than 1 DWPD and 99% up to 5 DWPD. It is projected that fewer than 1% of applications will need >10 DWPD by 2022, demonstrating a shift to READ-intensive SSD technology. It is hard to imagine today's 100TB data lake being built with slow hard drives over modern 3- and 4-bit SSDs based on cost, performance, and reliability.

Let's explore the meaning of an SSD wearing out by reviewing its warranty. Samsung's 480GB 2½" SATA-3 SSD SM883 has a DWPD of 3.0 and a 5-year warranty – a useful life of:

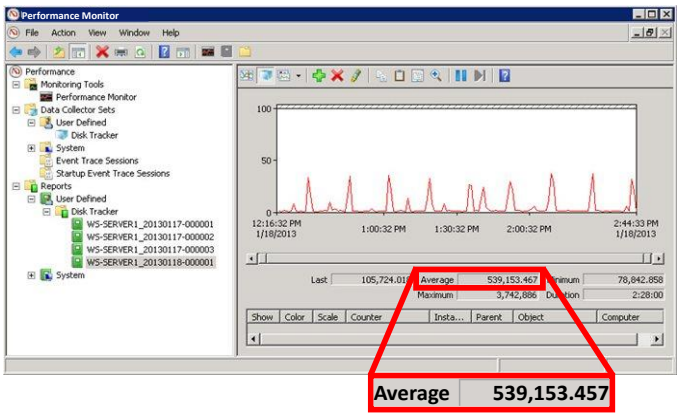
480GB x 3 DWPD x 365 days a year x 5-year warranty = 2,628,000GB.

Over 2.6PB can be written to this drive under warranty – a lot of data! Assume you need to write 500GB a day to this drive for 60 months, this table shows there's a lot of useful drive life left and it would likely last you an additional 60 months.

Month	GB/day	Total GB	GB remain
1	500	2,628,000	2,613,000
2	500	2,613,000	2,598,000
3	500	2,598,000	2,583,000
⋮	⋮	⋮	⋮
60	500	1,743,000	1,728,000

TLC and QLC have the same sequential READ speed, so the key to selecting the right SSD model for your application or system is to know the average number of bytes written in a day.

Begin an analysis by collecting data on the most active day using Window's PerfMon or the Linux's *sar* or *iostat* command to report on the average number of bytes written per second.[66] Extrapolate it out for one day – a system that writes 539,153 bytes per second (540,000 rounded) x 60 seconds per minute x 60 minutes per hour x 24 hours per day, or



540,000 x 60 x 60 x 24 = 46,656,000,000 bytes of data written per day.

Convert that to gigabytes and you get 43GB/day. On an annual basis,

43.45GB x 365 = 15,859GB/year or 15.49TB/year.

If the drive has a 5-year warranty,

15.49 x 5 years = 77.45TB/drive warranty period.

A 77TB warranty is sufficient. Anything less and you are buying the wrong SSD. The paper cited earlier, "*Understanding Windows Storage IO Access in the Age of SSDs*", has additional examples.[67] If you are using a Redundant Array of Independent Disks (RAID) to protect against drive failures, you are further protected against data loss. Intel and others often add SLC cache to QLC SSDs to increase the device's useful DWPD warranty life and also boost performance.[68]

As a general rule-of-thumb[69]:

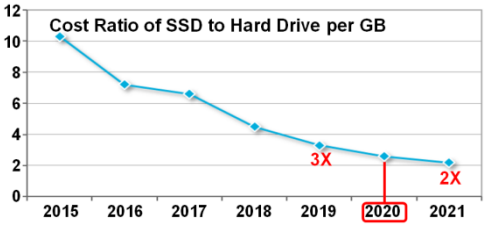
Use Case	**Approx. SSD DPWD**
Boot Drive	0.1 ~ 1.0 random
Content Distribution	0.5 ~ 2.0 sequential
Virtualization and Containers	1.0 ~ 3.0 random
OLTP Database	~ 3.0 random
High Performance/Caching	~ 3.0 random

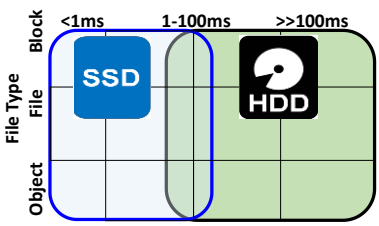
Understanding QLC Data Profiles - What Workloads Work Best?

The 8430 or DMX-4 had many 10K RPM hard drives that reflected a compromise between very expensive and small 15K RPM and even slower but cheaper and larger 7.2K RPM drives. Businesses opted to make this concession because they were budget-constrained and many applications did not need 15K RPM drives. As a result, data workload classification employed tiers of fast and slow hard drives in different RAID types. Administrators faced with solving ultra-fast low-latency business problems may have even used "short-stroke" hard drives.

A few years ago, voluminous read-only data was relegated to large 8-14TB hard drives or even magnetic tape. As capacity requirements grew and new storage projects arose, the need for lower cost, greater reliability and speed improvement found organizations replacing hard drives with QLC SSDs. A server such as Dell's R720xd with 24 x 2½" front-drive slots might use 2TB 7.2K SATA hard drives. They could be replaced by just 8 x 2½" 8TB QLC SATA SSDs for 64TB of capacity (38% more) and 720,000 4K random READ IOPS (375 times more), saving on power and cooling, and providing **16 open slots** for future expansion.[70] With a full set of 24 QLC drives, it could deliver two million IOPS and 768TB of capacity with 4:1 compression techniques and provide a fast storage platform for analytics, CEPH, NoSQL, and big data applications.

Trend lines show that customers who still buy hard drives are part of a shrinking minority. Just like vacuum tubes gave way to transistors, the world is surely heading to SSDs. Hybrid systems of hard drives and SSDs made great sense when SSDs had a small capacity and were expensive, but now their sizes rival and exceed hard drives while their cost profile had been steadily decreasing and now hovers at just over twice the price.[71] That does not mean hard drives will become extinct since there will continue to be use cases for inexpensive spinning media.

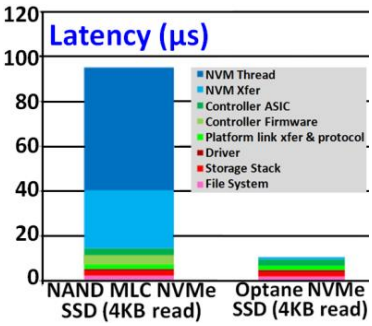




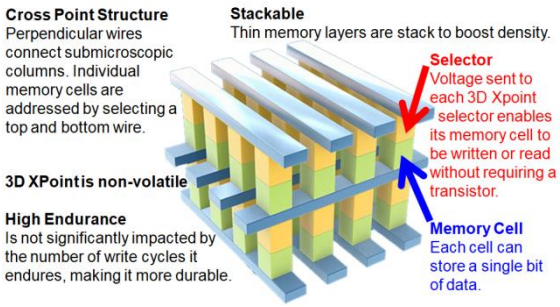
Intel Optane

From an endurance perspective, QLC NAND is a good fit for READ-intensive environments. But what would you choose if you needed WRITE-intensive ultimate performance storage? A few years ago, an SLC NAND would be a good solution, but now there is a superior technology.

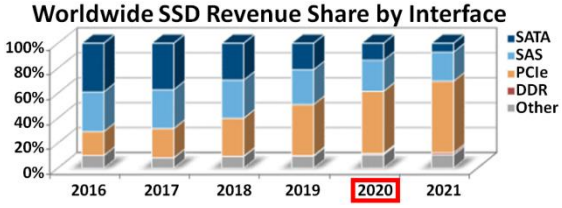
Optane is Intel's brand name for 3D XPoint (pronounced "cross point") transistor-less technology co-engineered with Micron. It is a low-latency non-volatile memory that is faster than NAND and supports near-infinite WRITE endurance. Fear of prematurely wearing it out is unwarranted since the U.2 DC D4800X is rated for 60 DWPD versus 3 DWPD for a NAND SSD.[72]



3D XPoint uniquely stores binary values making it an excellent choice for WRITE-intensive database redo logs or caching.[73] It is 4X–10X faster than NAND, consumes less power and permits a cell to be both addressed individually and overwritten/updated removing the need for garbage collection. Micron's QuantX implementation is rated for 2.5M IOPS, supports 9GB/s of READ/WRITE bandwidth, and has latency under 8µs compared to 95µs MLC NAND.[74,75] It doesn't need a reserve capacity and may only need a limited ECC.



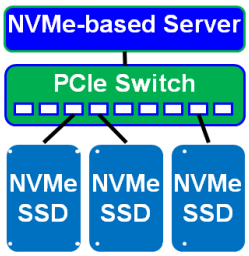
Unlike NAND, Optane does not have a control gate, oxide barrier or use FNT to move electrons. When a voltage is applied to a selector's top and bottom wire, one cell is read or written in contrast to a NAND's page at a time approach. Using a Phase Change Memory (PCM) such as chalcogenide glass, the state of the glass is altered from amorphous (clear or 0) to crystalline (opaque or 1) like a re-writeable recordable DVD.[76,77] It is dense when stacked in a grid of 128 billion cells per die.[78,79]



Storage evolution trends are clear and the revenues generated by these products are undeniable. This IDC chart shows PCIe storage will reach over 60% market share this year as older SSD technologies age out.[80]

What's new in storage?

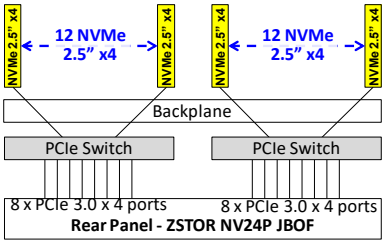
NVMe and Just a Bunch of Flash

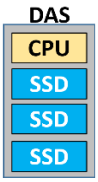


As discussed, NVMe slashes latency, supercharges parallelism and significantly improves SSD throughput beyond the hard drive architecture. Rather than attach and funnel data through a SAS/SATA controller, NVMe SSDs connect at PCIe speed to the CPU. One such NVMe SSD design outside the server is "Just a Bunch of Flash" or JBOF. JBOFs do not use RAID controllers but present NVMe SSDs to a processor over a PCIe bus. Servers run software to manage SSDs as if they were direct attached.

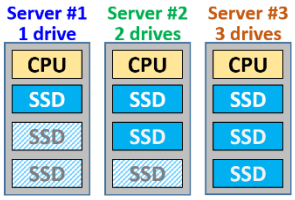
JBOF is neither a SAN nor an HCI since it doesn't share resources, lacks thin provisioning, hardware RAID protection, high-availability, and other typical storage array functionality. JBOF is for ultra-high performance, low latency use cases where there are more devices than server

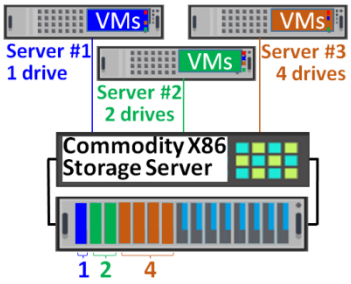
slots, such as with a blade server. SuperMicro's JBOF uses 32 EDSFF E1.L rulers through 64 PCIe lanes to share 64GB/s of throughput among 8 different servers.[81] As shown, ZSTOR's 24 NVMe SSD's on 4 lanes can assign groups of up to 12 drives to 8 hosts through PCIe switches.[82]





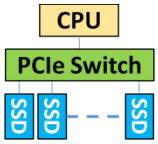
For decades, the Direct Attached Storage (DAS) model shown to the left incorporated drives in the server's chassis for optimal performance and simplicity.[83] While easy, one server might have excess unused capacity and another might be out of space. On the right, **server #1** has two unused SSDs, **server #2** has one unused SSD and **server #3** uses all three. If **server #3** needs a fourth drive, it has no open slots. For this and other reasons such as ease of management, classic SANs came to be.





By placing SSDs into a JBOF, drives are allocated as needed as shown to the left. In this case, it is easy to assign a **single drive** to **server #1**, **two** to **server #2**, and **four** to **server #3**. With room for future growth, no waste and no inter-server Ethernet latency, JBOFs are a low-cost approach to creating a Software-Defined Storage SAN.

As shown to the right, JBOF designs can also be scaled beyond a one-to-one host and target relationship using an ultra-low latency PCIe switch. Multiple switches can also help create a highly available JBOF storage system.

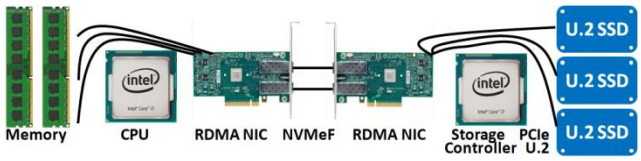


NVMe Over Fabrics

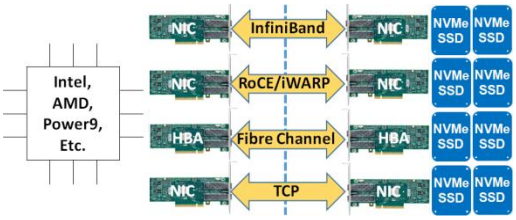
With designs such as HCI, applications may run slower if the CPU is taxed when sending large amounts of data to storage. It happens when the inter-server transmission uses a high overhead protocol such as TCP/IP across a small bandwidth network. Some companies addressed this by adding servers and distributing the workload accordingly. Newer HCI designs use NVMe over Fabrics (NVMeF) - an ultra-low latency, high throughput solution that frees the CPU of a lot of overhead and allows SSDs to be on a network outside of a server's PCIe bus similar to JBOF.

NVMe was designed to use a reduced latency Remote Direct Memory Access (RDMA) protocol allowing a storage device to receive data from main memory without cache, CPU, or operating system involvement. RDMA allows two servers to share data in their memory without using CPU cycles, allowing the processor to focus on application processing. In its simplest form, there is a

pointer to data to be moved, a pointer to where it should go, and a quantity. The CPU bypasses TCP/IP and doesn't use I/O cycles on SATA or SAS host adapters - the essential difference between NVMe and SCSI.[84] RDMA copies data to or from an SSD to the processor's memory over a network using RDMA-ready adapters as shown here.[85]

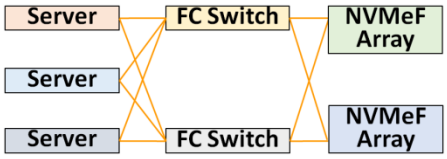


NVMeF leverages RDMA over an existing Fibre Channel (FC), Ethernet, Internet Wide-Area RDMA Protocol (iWARP), or InfiniBand network. With Ethernet, RDMA employs Converged Ethernet or RDMA over Converged Ethernet (RoCE pronounced "Rocky"). Converged Ethernet uses RDMA on the same Ethernet switches and cables a customer already owns and TCP uses existing NIC cards.



NVMeF achieves the performance of direct-attached SSDs while sharing a standard SCSI network. The difference between local and NVMeF-attached storage was minimized and adds less than 3% or <10µs of latency to the CPU-storage path including end-to-end switching.[86] NVMe SSDs are addressable over a server's PCIe bus or through NVMeF.[87]

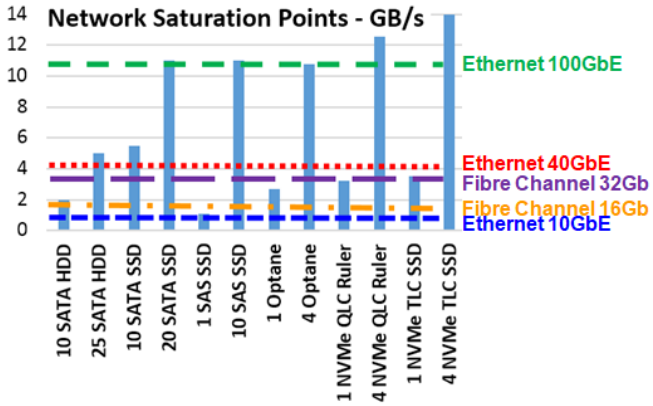
Like today's iSCSI, NVMeF is a protocol that enables the communication between a host and network-attached storage at near-peak performance, so an existing network must be fast enough to support it. Fibre Channel needs a minimum of 16Gb and ideally 32Gb, and NIC cards need to run at 25Gb, 40Gb or 100Gb with upgraded software drivers. There is support for older SCSI protocols and NVMe over the same fabric, but the greater the number of high speed drives you concurrently support, the greater the number of paths needed.



A New Bottleneck – The Network

The architectural shift to faster SSDs has not been uniform. Last decade's all-flash storage arrays brought about lower latencies, higher bandwidth, greater throughput, increased density, greater virtualization, higher server/CPU/license utilization, as well as power, cooling, space, and administration savings. Unfortunately, it also caused the network to become the new bottleneck. Ethernet, FC and other network topologies we have relied on for decades turn out to be performance killers with many active SSDs. As a result, processors and applications that relied on SATA and SAS arrays for I/O still waited for data.

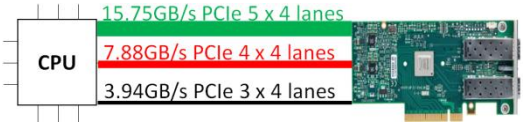
A storage device rarely approaches theoretical performance levels on a day-to-day basis. A ten-year-old SAN could support many simultaneous 100-200MB/s hard drive transfers but ran into bottlenecks with a similar number of 550-1,100MB/s SSDs. A single 3,500MB/s NVMe SSD's theoretical throughput is throttled by 75% on an 8Gb/s FC, 50% on a 16Gb/s FC link, and could nearly saturate a single 32Gb/s FC link. This chart plots hard drives, SSDs, EDSFF rulers and Optane drives against transfer rates.[88] It shows the limitation of **10**, **40** and **100**Gb Ethernet and **16Gb/s** and **32Gb/s** FC as full throughput is reached by a handful of high performing drives. A single SATA SSD runs fine on a 10Gb/s network while a bunch of them could saturate it. The same is true for NVMe SSDs. Just one NVMe drive likely runs fine on a 25-gigabit link but with a bunch of very active drives, their high performance will be slowed by that link speed. Individual **100GbE** ports will bottleneck four NVMe TLC SSDs at theoretical transfer rates. The optimal networking solution for NVMe is a 400GbE switch.



Modern motherboards and processors using four **PCIe 3.0** bidirectional lanes can provide **3.9GB/s** (3,900 gigabits) of bandwidth, or about the capability of one NVMe SSD. Just 6 NVMe drives running at full capacity makes PCIe a new bottleneck and would limit the number of active Ethernet or other devices that share these lanes.[89] In other words, a server reading a lot of NVMe data could lack the resources to transmit those results anywhere else. It is worth noting that EDSFF drives are PCIe 4.0 and 5.0 ready.

Year	PCIe	Bandwidth GB/s 1x	Bandwidth GB/s 2x	Bandwidth GB/s 4x	Bandwidth GB/s 8x	Bandwidth GB/s 16x
2010	3	0.98	1.97	3.94	7.88	15.80
2017	4	1.97	3.94	7.88	15.75	31.50
2020	5	3.94	7.88	15.75	31.51	63.00

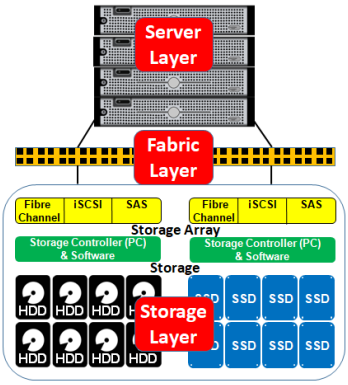
PCIe 4 doubles the bandwidth to **7.88GB/s** allowing SSDs to use fewer lanes. As a result, a system could support more drives or have active SSDs get more parallel work done.[90] **PCIe 5** again doubles the bandwidth to **15.75GB/s**. This line thickness diagram shows the amount of I/O traversing the CPU and RDMA adapter at each PCIe revision.



A single 32-ruler PCIe 4.0 4K movie content delivery server lacks the bandwidth and processor power to simultaneously stream 64,000 movies ($102\text{GB/s or } 3{,}200\text{MB/s} \times 32$) since it also needs multiple 100Gb/s Ethernet NICs that also consume PCIe resources. With 8K movies, 4X more bandwidth is needed and mapping one Ethernet or FC link to one NVMe QLC SSD for movie streaming becomes impractical.[91]

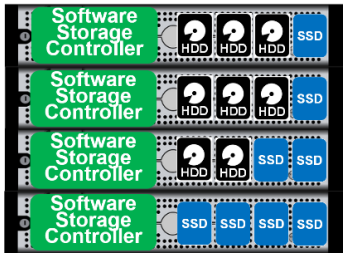
The good news is that for the most part, SSDs do not run at theoretical maximums and when NVMeF was benchmarked against SCSI over 32Gb/s FC, it provided 58% more IOPS with 11-34% lower latency.[92] Testing showed NVMeF added just 10µs of latency compared to 100µs for SCSI FC.[93] The Fibre Channel Industry Association also has plans for 128Gb/s and the Ethernet roadmap calls for faster 200Gb/s speeds.[94,95]

Software-Defined Storage



Three-tier SANs have been a staple of data center architecture for twenty years as storage demand grew faster than server drive slots. DAS issues of unused capacity were addressed through Ethernet and FC networks that provided storage pooling, LUN assignment, independent vendor choice for each tier, and more. In a storage array, the software runs on a processor that handles incoming host I/O requests and other management functions. Those requests may flow through switches to aid resource sharing.

SDS is viewed as a lower cost SAN without vendor hardware lock-in, offering substantial OpEx and CapEx savings, reducing storage provision time, and simplified management compared to a SAN.[96] SDS is a loose definition that abstracts traditional hardware-based storage services to manage internal or external virtualized storage resources. It was designed to automate daily configuration, tuning tasks, and abstract storage services, making it possible to have a Software-Defined Storage network made up of multi-vendor commodity servers from Dell Technologies, HPE, Lenovo, and others.

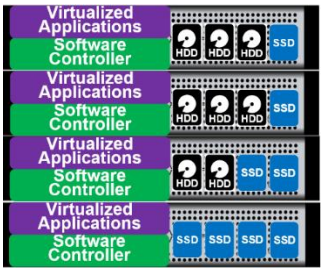


Converged Infrastructure (CI) and HCI began over a decade ago as an easy way for companies to consume prepackaged software, servers, networking, and storage SAN components. HCI shrunk the SAN design into an all-in-one set of clustered server nodes that pool virtualized compute and storage resources. Both approaches allocate storage from internal disks on demand through software to local server applications or non-participating servers as though they came from a storage array such as a Dell EMC Unity.

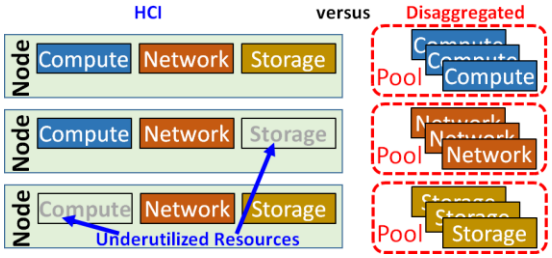
As application virtualization became popular, CI and HCI using SSDs and cloud computing brought about further design changes. Increases in storage speed and density, ease of administration, provisioning, compression/deduplication, replication, snapshots, and other enhancements also helped change storage architectures. Storage virtualization became popular

with the rise of iSCSI instead of expensive and complex FC networks and harder to manage hardware-based storage arrays. While it may not be the right design for every organization, SDS uses commodity large memory multicore servers to manage storage resources and provide SAN functionality by divvying out storage from a pool of shared low-cost, high-capacity internal hard drives and SSDs.

Solutions such as VMware's vSAN, open-source Ceph, and others mimic a SAN through a suite of enterprise software services. They support several storage options and have an Application Programming Interface (API) to control storage under software control. The storage devices that physically resided in the storage array are now found in the server's drive slots. The storage array software now runs on server cores to handle incoming and outgoing requests and storage network routing. Using standard cables, data is presented to other hosts using standard protocols like iSCSI. SDS may run virtual applications, offer policy-based storage to handle different requirements, provide file and block capabilities, and come pre-packaged as an appliance or as software-only.

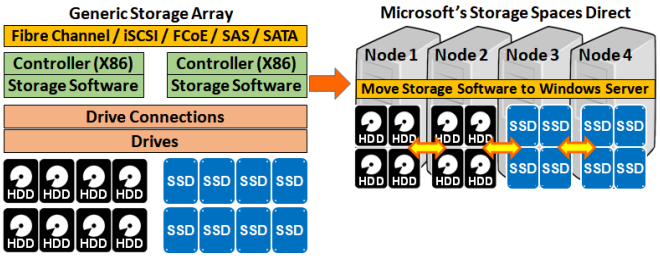


A key SDS/HCI advantage is to get the storage closer to the processor, thereby reducing some of the latency found in a traditional SAN. Without needing to packetize and traverse a network to get to the storage, the CPU wait time is reduced allowing them to be more productive. With QLC SSDs able to cost-effectively replace hard drives, applications can easily gain a multi-fold performance increase.



With **HCI**, if you are short of compute or storage, you add another node. This can run into scenarios where compute-heavy environments have extra unused storage or storage-heavy workloads with unused compute cycles. These wasted, imbalanced set of resources can also slow down the entire complex if they experience higher inter-node latency. To address this issue, a **Disaggregated Infrastructure** (**DI**) two-tier application and storage server design was created.[97] **DI** allows software control of compute, network and storage pools to be dynamically combined and independently scaled using low-latency, high-bandwidth connections such as NVMeF. For example, an application needing 4 or 40 processing cores and 10 to 1000TB of storage could be policy provisioned on the fly from full-featured pools of multi-sized multi-vendor media. Unused resources are returned to their pool. The cluster can be large and it gains performance and capacity as resources are added to the grid.

Microsoft's Storage Spaces Direct (S2D) is a Windows Server 2019 SDS capability that provides traditional 3-tier SAN features at no charge.[98] Storage controller and storage functionality are moved into the cores running Windows servers. S2D scales to 16 Ethernet nodes and 400+ drives using node-based erasure coding data protection.[99] Erasure coding spreads data blocks and parity across nodes rather than use local disk group parity RAID reconstruction. S2D is a disaggregated storage cluster or an HCI storage/compute Hyper-V virtual machine platform. Four storage nodes can be created in just three steps:




```
#1 Create cluster       New-Cluster –name MyCluster –Node "N1", "N2", "N3", "N4" –NoStorage
```

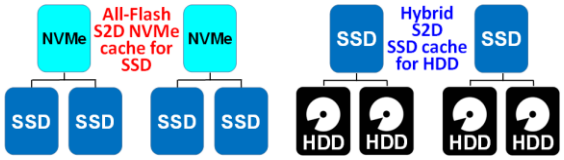
And enabled:

```
#2 Enable S2D           Enable-ClusterS2D
```

A 1TB volume is created from the new cluster containing two storage tiers - a 100GB SSD-based **`performance`** tier and a 900GB hard-drive-based **`capacity`** tier:

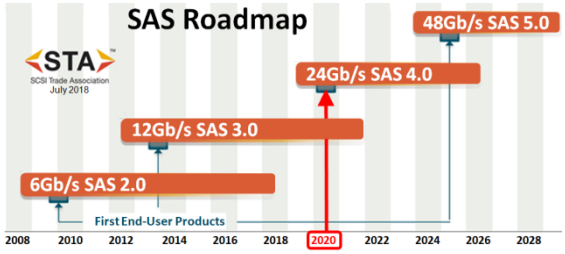
```
#3 Create a volume      New-Volume –StoragePoolFriendlyName S2D* -FriendlyName vDisk1 FileSystem
                        CSVFS_REFS – StorageTierFriendlyname Capacity,Performance –
                        StorageTierSizes 900GB, 100GB
```

A new auto-tiered storage volume can be provisioned to other servers from a mix of cluster-based SSDs and hard drives. Various vendors offer pre-built S2D appliances such as Dell's Ready Nodes. Microsoft also has approved **all-flash** and **hybrid** designs using a mixture of SATA, SAS and NVMe drives.



SAS-4

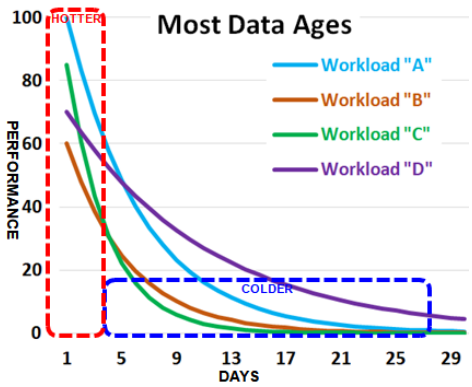
NVMe has revolutionized flash storage, but it doesn't mark the end of SAS. SAS-4 was introduced this year with **24Gb/s** PCIe 4.0 support.[100] The popular SAS-3 bandwidth could be saturated by a handful of very active SSDs.[101] SAS-4 helps existing users since the controller is backward compatible with SAS-3 (12Gb/s), SAS-2 (6Gb/s) and SATA-3 (6Gb/s) drives and cables. SAS-4 doubles the lane bandwidth and allows an SSD to use 2 or 4 serial links. When PCIe 5.0 is available this year, a SAS-4 SSD can map to a single 3.9GB/s lane.[102] IDC predicts SAS-4 will remain a popular drive standard due in part to its compatibility with the installed base of older supported devices.[103,104] From a performance standpoint, many SAS customers may find high performance (versus ultra-high performance) sufficient.



Storage Lifecycle Automation – Rebalancing SSD-based Storage

There have been numerous studies going back a decade or more showing that data follows a lifecycle. It is created, perhaps cleansed, processed, turned into information, transmitted, and likely becomes stale. While not a rule and there are many exceptions, data can start on a lifecycle journey in anywhere from 3 to 30 days.[105] Time since last accessed, time since last modified and time since creation helps form common age-related data tiering policies. Data comes in all formats and classifications such as structured and unstructured and can have implied importance such as a business contract, transaction, email, and more. Data designated as stale can also become critical to an organization in a very short order.

Each policy step aligns data in its lifecycle to the performance, price and protection scheme of appropriate storage. Data such as medical X-rays can follow a policy that places new images on a fast and expensive storage tier since it is frequently accessed during patient treatment, and moved to a slower, lower-cost or archival tier when they are discharged. Implementations such as EMC's Fully Automated Storage Tiering (FAST) from 2009 automatically demoted **inactive or less active data** to **slower hard drives** and promoted **very active data or fresh data** to **faster devices**. In this example, four hypothetical workloads have similar yet different profiles. **Workload "A"** starts on the fastest tier for the first few days before its activity gradually drops off and it is migrated to a slower tier. **Workload "C"** has a longer active cycle before its usefulness drops off. Some customers found their **very active hot data** represented just 5% of their total capacity, which of course is the exact use case for tiered storage and maximizing TCO.[106]



The original SSD/hard drive hybrid array was at times met with concern over uneven performance if needed data was on the wrong tier, leading some to an expensive single-tier all-flash array. However, enterprise storage is limited by budget, physical space, and other constraints. Storage rebalancing or tiered hybrid arrays are making a comeback spurred on by:

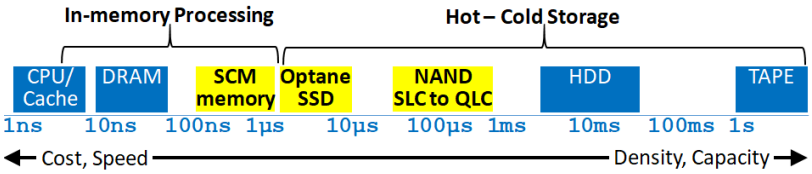
1. Optane/SCM/NVMe for super-fast high-activity data,
2. NVMe/SAS/TLC for moderately active data, and
3. QLC SSDs or cloud for super-dense or infrequently accessed data.

These all-solid-state arrays are dispelling the original concerns. Artificial intelligence techniques now predict usage patterns and position data on the appropriate tier as performance, price, capacity, and other attributes again create device differentiation.

Using the cloud for inactive data is gaining popularity despite its higher latency since the data is regarded as cold. Organizations should keep an eye on high public cloud egress charges based on access patterns and decide if an in-house QLC tier is more appropriate.

Tiers are also appearing inside the device. Intel's H10 M.2 hybrid combines Optane with QLC NAND and appears as a single drive to the operating system.[107] Toshiba's XL-Flash SSD uses an SLC "hot data" write cache and a "cold data" TLC or QLC persistent layer for ultralow READ latency and greater random READ IOPS. Samsung's "TurboWrite" and Micron's "Dynamic Write Acceleration" automatically use NAND as an SLC cache to increase the DWPM since controller logic dictates what is written and how often it is destaged to multi-level cells.[108,109]

Storage Class Memory



Regardless of processor speed, if instructions aren't in its registers, they load from slower subsystems. A CPU can add two numbers in less than one nanosecond, but it can take 10 nanoseconds or more when values come from memory and much longer if retrieved from a storage device. During the time a processor makes one memory access, it could have completed ten simple instructions.[110] The fastest SSD is 10,000 times slower than adding two numbers, and if the value comes from a hard drive, it would be about four million times slower.

An Intel breakthrough leveraged 3D XPoint to create an ultra-fast high capacity DDR4 persistent memory and storage technology. With DRAM-like speed and 10X lower latency than an SSD, Storage Class Memory has a READ latency of 350ns positioning it as slower than DRAM (<100ns) but faster than SLC NAND (<100µs).[111] SCM can act like an SSD, is READ/WRITE byte-addressable as memory, and dramatically more resilient than QLC NAND (30-60 DPWM vs. .3-.8 DWPM).

This gives rise to a technique called computational storage with applications processing in a non-volatile storage layer rather than in classical volatile memory.[112] In essence, once the computation is complete, data does not have to be transferred to a physical SSD or hard drive.

SCM's main drawback is cost. Since SCM is ten times more expensive than NVMe SSDs, it is possible to build a multi-tier hybrid storage array with a small amount of SCM in the first tier. SCM could also be used as a burst buffer for unforeseen activity spikes in a storage array with

only slower and cheaper QLC NVMe NAND for traditional storage.[113] In another use case, if applications leverage SCM to extend their memory space, a software-controlled SCM could destage virtualized storage containers to QLC SSDs over 10µs NVMeF with the host never issuing a direct write to a QLC device.

Relying on SCM as a burst buffer greatly extends QLC DWPD limitations. With compression and deduplication, it would provide organizations with a new ultra-fast, very low-cost, petabyte-capable approach to storing data. With software intelligence powering the SCM-QLC interaction, very low-cost QLC 2½" drives or more expensive but larger capacity EDSFF rulers could bring prices down to or below the $0.03/GB level of hard drives, especially when JBOFs are used. Issues caused by write amplification would also be addressed by software destaging logic.

Traditional software management of the QLC drives would be greatly minimized, "archival" data could stay in place on the QLC drives, tiering would be eliminated, drives sizes and brands could be mixed, and the data could be used for all types of file access. Presently, Intel, Micron, Samsung (Z-NAND), SK Hynix (3d XPoint-like), and Western Digital (ReRAM) make SCM.[114]

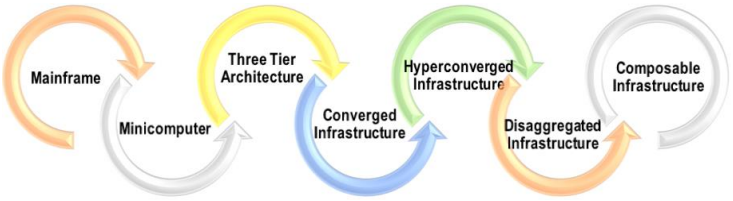
Conclusion

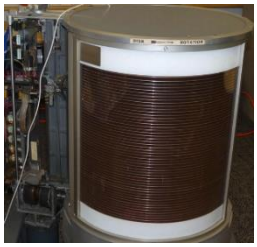
Enterprise storage continues its journey of never-ending innovation. The data center is like a living, breathing organism that devours speed and power, and must evolve along with our emerging digital economy to keep up with an ever-increasing workload and requirement transformation. Our world uses many multi-dimensional emerging trends, some evolutionary and others are disruptive. It would be nearly impossible to offer ground-breaking dynamic streaming, business analytics, Internet of Things, big data, machine learning and other concepts using a twenty-year-old design. We are on the cusp of amazing 3D chips that demand new approaches to efficiently solve today's enterprise computing problems, advances in the cloud paradigm, and futuristic architectures beyond hyperconverged called disaggregate and composable using NVMeF interconnects. There's even more to come.

Enterprise primary storage, which focuses on large organizations with scalable products and services associated with processing and retrieving data, is about to be reinvigorated with new storage devices nicknamed rulers, new standard protocols like NVMe, and insanely fast exabyte storage racks with ever-decreasing latencies. This new era of storage replaces yesterday's numerous bulkier, smaller SAS/SATA SSDs and hard drive racks with far more elegant, reliable,

faster and more cost-effective solutions. More layers, greater density, faster throughput, newer storage concepts, and lower cost make any hard drive comparison simply unfair, although it will still take years for them to go away. Eventually, SSDs will cost the same as hard drives, and that will likely seal their fate once-and-for-all. And this is just the beginning.

Each new generation of enterprise storage builds on the foundation of what has preceded it, bringing higher performance and lower power consumption along with more host operating system and virtual application controls. Just like the computing world's journey of mainframes, minicomputers, and composable infrastructures, the world of enterprise storage's journey included its humble beginnings of punch cards, paper tape, magnetic tape, one ton 4MB drives, removable packs, SSDs and even cloud storage.[115,116] SSDs have gotten bigger and faster, and compared to the DMX-4's first SSD, today's best drives hold 2000 times more and deliver it 70 times faster for a fraction of the price.[117]





Occasionally these paths overlap as in the case of server-based storage, software-defined storage, and the cloud. Enterprise customers choose between storage models and determine what fits best with their budget and technical savvy. Part of today's choice comes from a reaction to future-hype, the decline of NAND prices, increased density, dramatically higher performance as influenced by Moore's Law, and ease-of-use. Everything must change.

Footnotes

[1] http://www.cnn.com/TECH/computing/9902/24/p3next.idg/index.html
[2] https://www.zdnet.com/product/dell-dimension-4300/
[3] https://www.emc.com/collateral/hardware/white-papers/h6206-symmetrix-vmax-microsoft-sql-server-wp.pdf
[4] https://www.questsys.com/files/Master-EMC-Price-List.pdf
[5] https://www.amazon.com/s?k=SDCZ800-128G-G46&i=electronics&ref=nb_sb_noss
[6] https://www.dellemc.com/en-us/storage/vmax-all-flash.htm
[7] https://www.dellemc.com/en-us/storage/powermax.htm
[8] https://www.engadget.com/2018/07/20/toshiba-flash-166-gb-per-chip/
[9] https://www.statista.com/statistics/398951/global-shipment-figures-for-hard-disk-drives/
[10] https://www.forbes.com/sites/tomcoughlin/2018/01/17/toshiba-western-digital-and-seagate-products-at-the-2018-ces
[11] https://www.architecting.it/blog/wd-20tb-hdd
[12] https://www.statista.com/statistics/285474/hdds-and-ssds-in-pcs-global-shipments-2012-2017/
[13] https://hexus.net/tech/news/storage/123953-seagates-hdd-roadmap-teases-100tb-drives-2025/
[14] https://www.anandtech.com/show/15117/demand-for-hdd-storage-booming-240-eb-83-million-drives-shipped-in-q3-2019
[15] https://www.anandtech.com/show/14903/intel-shares-new-optane-and-3d-nand-roadmap
[16] https://www.theregister.co.uk/2018/08/14/prepare_for_100tb_ssd/
[17] https://blog.westerndigital.com/speeds-feeds-and-needs-latency/
[18] https://en.wikipedia.org/wiki/SCSI
[19] https://en.wikipedia.org/wiki/U.2
[20] https://www.intel.com/content/www/us/en/products/memory-storage/solid-state-drives/consumer-ssds.html
[21] https://edsffspec.org/
[22] https://venturebeat.com/2019/11/04/edsff-in-action-flash-storage-capacity-like-youve-never-seen/amp/
[23] https://www.anandtech.com/show/13218/ssd-form-factors-proliferate-at-flash-memory-summit-2018
[24] https://www.samsung.com/semiconductor/ssd/nf1-ssd/
[25] https://www.samsung.com/semiconductor/global.semi.static/Whitepaper_Samsung_NGSFF_SSD_1809.pdf
[26] https://en.wikipedia.org/wiki/Serial_ATA
[27] https://venturebeat.com/2019/10/18/nvme-vs-sata-which-nand-storage-do-you-need/amp/
[28] https://en.wikipedia.org/wiki/Port_multiplier
[29] http://www.scsita.org/content/wp-content/uploads/2018/12/STA_Q4_2018_BrightTalk_v3.pdf
[30] https://www.marvell.com/documents/rvy6gdwqcx61ryowafdr/
[31] https://storage.toshiba.com/docs/life-after-sata-documents/comparing_ssd_interfaces_best_practice.pdf
[32] https://cotscomputers.com/blog/pcie-lanes/
[33] https://www.amd.com/en/processors/epyc-7002-series
[34] https://nvmexpress.org/about/
[35] https://www.nvmexpress.org/wp-content/uploads/NVMe_Overview.pdf
[36] https://www.nvmedeveloperdays.com/English/Collaterals/Documents/Report_State_of_NVMe_201805.pdf
[37] https://www.theregister.co.uk/2015/05/08/taming_the_flash_card_cowboys/?page=2
[38] https://flashmemorysummit.com/English/Conference/Keynotes.html
[39] https://www.marvell.com/documents/rvy6gdwqcx61ryowafdr/
[40] https://itpeernetwork.intel.com/why-you-should-care-about-nvm-express/#gs.kny29r
[41] https://www.seagate.com/files/www-content/product-content/ssd-fam/nvme-ssd/nytro-xf1440-ssd/_shared/docs/nvme-performance-tp692-1-1610us.pdf
[42] https://www.tomshardware.com/news/pcie-4.0-5.0-pci-sig-specification,38460.html

[43] https://www.idc.com/research/viewtoc.jsp?containerId=US44383918
[44] http://www.ni.com/product-documentation/10126/en/
[45] https://www.gamersnexus.net/guides/1497-ssd-architecture-1-what-is-tlc-nand-mlc-anatomy/Page-2
[46] https://www.dellemc.com/vi-vn/collaterals/unauth/white-papers/products/storage/h14920-intro-to-vmax-af-storage.pdf
[47] http://investors.micron.com/news-releases/news-release-details/micron-ships-industrys-first-quad-level-cell-nand-ssd
[48] https://searchstorage.techtarget.com/answer/Where-is-QLC-NAND-the-most-useful-in-the-enterprise
[49] https://www.micron.com/-/media/client/global/documents/products/technical-marketing-brief/qlc_technology_high-level_tech_brief.pdf
[50] https://www.micron.com/-/media/client/global/documents/products/white-paper/ssds_and_windows_monitor_storage_io_white_paper.pdf
[51] https://www.micron.com/-/media/client/global/documents/products/technical-marketing-brief/qlc_technology_high-level_tech_brief.pdf
[52] https://venturebeat.com/2019/12/06/tlc-vs-qlc-nand-pick-the-best-memory-technology-for-your-application/amp/
[53] "Inside Solid State Drives (SSDs)" by Rino Micheloni, Alessia Marelli, and Kam Eshghi. ISBN 978-981-13-0598-6. P. 52
[54]https://www.eetimes.com/author.asp?doc_id=1282825
[55] https://www.tweaktown.com/news/62984/intel-micron-qlc-flash-yields-less-50/index.html
[56] https://www.anandtech.com/show/14903/intel-shares-new-optane-and-3d-nand-roadmap
[57] https://www.anandtech.com/show/7237/samsungs-vnand-hitting-the-reset-button-on-nand-scaling
[58] https://arxiv.org/abs/1807.05140
[59] Luo, Y., Ghose, S., Cai, Y., Haratsch, E.F., & Mutlu, O. (2018). Improving 3D NAND Flash Memory Lifetime by Tolerating Early Retention Loss and Process Variation. POMACS, 2, 37:1-37:48.
[60] https://arxiv.org/abs/1807.05140
[61] https://www.elinfor.com/news/as-96-layer-3d-flash-memory-capacity-increasing-ssd-prices-will-continue-to-decline-p-11053
[62] https://www.flashmemorysummit.com/English/Collaterals/Proceedings/2018/20180808_FTEC-201-1 Yoon.pdf
[63] https://www.extremetech.com/computing/170748-how-long-do-hard-drives-actually-live-for
[64] https://documents.westerndigital.com/content/dam/doc-library/en_us/assets/public/western-digital/collateral/tech-brief/tech-brief-matching-ssd-endurance-to-common-enterprise-applications.pdf
[65] https://www.micron.com/-/media/client/global/documents/products/white-paper/ssds_and_windows_monitor_storage_io_white_paper.pdf
[66] http://blog.whitesites.com/How-to-Measure-your-Server-s-Disk-Writes-for-SSD-consideration__634941054420312500_blog.htm
[67] https://www.micron.com/-/media/client/global/documents/products/white-paper/ssds_and_windows_monitor_storage_io_white_paper.pdf
[68] https://www.tweaktown.com/news/68942/intel-bring-next-level-qlc-performance-endurance-665p-ssd/amp.html
[69] https://documents.westerndigital.com/content/dam/doc-library/en_us/assets/public/western-digital/collateral/tech-brief/tech-brief-matching-ssd-endurance-to-common-enterprise-applications.pdf
[70] https://en.wikipedia.org/wiki/IOPS
[71] https://www.weka.io/wp-content/uploads/2018/04/HPE-Flash-Tech-Spotlight-Hyperion-Research.pdf
[72] https://www.intel.com/content/dam/www/public/us/en/documents/product-briefs/optane-ssd-dc-d4800x-product-brief.pdf
[73] https://www.intel.co.uk/content/www/uk/en/products/docs/memory-storage/solid-state-drives/data-center-ssds/optane-ssd-dc-p4800x-p4801x-brief.html
[74] https://www.networkworld.com/article/3449576/micron-finally-delivers-its-answer-to-optane.amp.html
[75] https://indico.cern.ch/event/723339/attachments/1718424/2773126/New_Storage_Technologies.pdf
[76] Intel has yet to disclose the nature of it's PCM. Some believe it uses chalcogenide glass and others believe it uses memristors. https://pcper.com/2017/06/how-3d-xpoint-phase-change-memory-works/
[77] https://en.wikipedia.org/wiki/Phase-change_memory
[78] https://blocksandfiles.com/2019/07/02/optane-dimm-access-modes/
[79] https://wccftech.com/intel-optane-ssd-dc-p4800x-revenue-quarter-3d-xpoint-roadmap/

[80] https://www.flashmemorysummit.com/English/Collaterals/Proceedings/2018/20180808_MRES-201B-1_Burgener.pdf
[81] https://supermicro.com/en/products/system/1U/136/SSG-136R-NR32JBF.cfm
[82] https://zstor.de/de/zstor-nv24p-jbof-nvme-flash.html
[83] https://nvmexpress.org/wp-content/uploads/NVMe-202-1-Part-1-JBOFs_Final.pdf
[84] https://www.youtube.com/watch?v=QAIAoNheX-8
[85] https://nvmexpress.org/wp-content/uploads/NVMe_over_Fabrics_Sept_2017_Brandon_Hoff.pdf
[86] https://searchstorage.techtarget.com/news/252454170/Broadcom-Emulex-flashes-Gen-7-Fibre-Channel-adapter-for-NVMe
[87] https://content.architecting.it/BRKWP0120_NVMe_In_The_Data_Centre_1_0.pdf
[88] https://www.datanami.com/2016/11/10/network-new-storage-bottleneck/
[89] https://www.servethehome.com/marvell-25gbe-nvmeof-adapter-prefaces-a-super-cool-future/
[90] https://www.tomshardware.com/news/ssd-pcie-4.0-phison-nvme,38418.html
[91] https://www.zdnet.com/article/why-sata-flash-drives-are-being-left-in-the-dust/
[92] https://demartek.principledtechnologies.com/Reports_Free/Demartek_NetApp-Broadcom_NVMe_over_Fibre_Channel_Evaluation_2018-05.pdf
[93] https://searchstorage.techtarget.com/news/450302190/NVMe-over-Fabrics-gathers-steam-for-flash-and-post-flash-devices
[94] https://fibrechannel.org/roadmap/
[95] https://ethernetalliance.org/technology/2019-roadmap/
[96] https://www.ibm.com/downloads/cas/D6BZ0ODY
[97] Intel white paper “Discover the Benefits of Software-Defined Storage” – registration https://plan.seek.intel.com/SDS_Whitepaper_Reg
[98] https://youtu.be/k1ElKuyZPJg
[99] https://docs.microsoft.com/en-us/windows-server/storage/storage-spaces/storage-spaces-direct-overview
[100] https://demartek.principledtechnologies.com/Demartek_Interface_Comparison.html
[101] https://www.microsemi.com/product-directory/storage/5440-serial-attached-scsi-technology-sas-4
[102] https://en.wikipedia.org/wiki/PCI_Express
[103] http://www.scsita.org/content/wp-content/uploads/2018/12/STA_Q4_2018_BrightTalk_v3.pdf
[104] https://demartek.principledtechnologies.com/Demartek_SAS_Applications_24G_2018-07.html
[105] https://searchstorage.techtarget.com/tip/Why-storage-tiering-is-necessary-now-more-than-ever
[106] https://www.datacore.com/software-defined-storage/
[107] https://www.digitaltrends.com/computing/intel-announces-optane-h10-memory-with-ssd/
[108] https://www.forbes.com/sites/tomcoughlin/2018/08/13/some-flash-memory-keynotes/
[109] https://www.tomshardware.com/news/toshiba-3d-xl_flash-optane,37564.html
[110] https://www.networkworld.com/article/3449576/micron-finally-delivers-its-answer-to-optane.amp.html https://www.upgreat.pl/uploads/AKTUALNOSCI/Prezentacje_Smaczne_kaski_w_menu_HPE_20170919/HPE_storage_20170919.pdf
[111] https://www.theregister.co.uk/2018/12/21/scm_power_to_the_max/
[112] https://www.elinfor.com/knowledge/handing-over-the-data-to-the-ssd-is-the-hottest-form-of-computational-storage-currently-p-11208
[113] https://blog.architecting.it/vast-data-launch/
[114] https://blocksandfiles.com/2019/07/01/sk-hynix-storage-class-memory/
[115] http://cs-exhibitions.uni-klu.ac.at/index.php?id=187
[116] https://mybroadband.co.za/news/hardware/132408-south-africas-first-computers.html
[117] https://www.mouser.com/datasheet/2/388/Zeus_3_5_Fibre_Channel_SSD_Product_Datasheet_Rev1--2992.pdf