PERSISTENT MEMORY PM SUMMIT

JANUARY 24, 2019 | SANTA CLARA, CA

Converging Memory and Storage

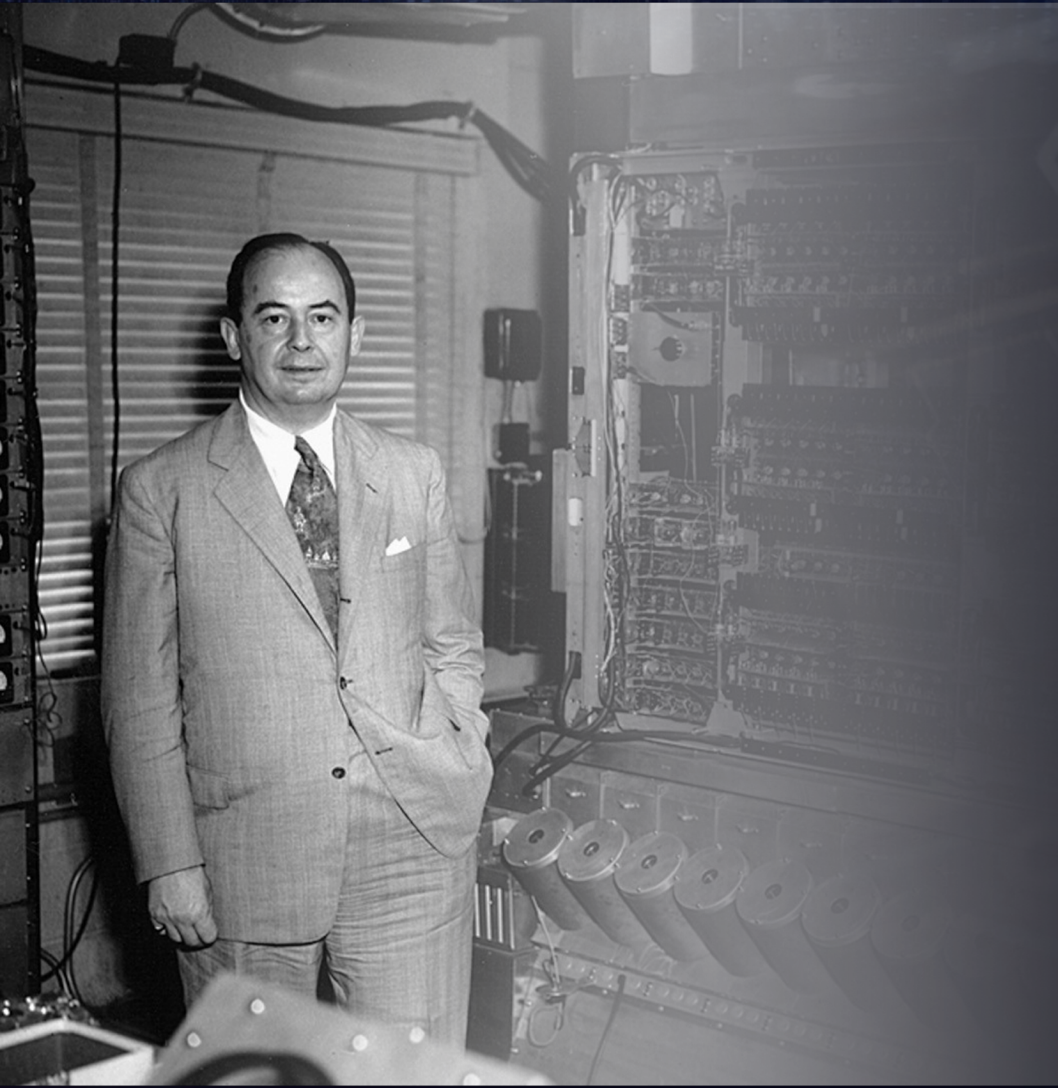
Frank Hady, PhD
Fellow, Intel Corporation
Chief Systems Architect, NVM Solutions Group

Disclosure

- PERFORMANCE RESULTS ARE BASED ON TESTING AS OF SPECIFIED DATES AND MAY NOT REFLECT ALL PUBLICLY AVAILABLE SECURITY UPDATES. SEE CONFIGURATION DISCLOSURE FOR DETAILS. NO PRODUCT CAN BE ABSOLUTELY SECURE
- THIS PRESENTATION INCLUDES FORWARD-LOOKING STATEMENTS RELATING TO INTEL. ALL STATEMENTS THAT ARE NOT HISTORICAL FACTS ARE SUBJECT TO A NUMBER OF RISKS AND UNCERTAINTIES, AND ACTUAL RESULTS MAY DIFFER MATERIALLY. PLEASE REFER TO INTEL'S MOST RECENT EARNINGS RELEASE, 10-Q AND 10-K FILINGS FOR THE RISK FACTORS THAT COULD CAUSE ACTUAL RESULTS TO DIFFER.

Notices and Disclosures

- [Performance results are based on testing as of [INSERT DATE] and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure.
- Software and workloads used in performance tests may have been optimized for performance only on Intel microprocessors. Performance tests, such as SYSmark and MobileMark, are measured using specific computer systems, components, software, operations and functions. Any change to any of those factors may cause the results to vary. You should consult other information and performance tests to assist you in fully evaluating your contemplated purchases, including the performance of that product when combined with other products. For more complete information about performance and benchmark results, visit http://www.intel.com/benchmarks]
- All information provided here is subject to change without notice. Contact your Intel representative to obtain the latest Intel product specifications, roadmaps, and related information.
- Intel technologies' features and benefits depend on system configuration and may require enabled hardware, software or service activation. Performance varies depending on system configuration. No computer system can be absolutely secure. Check with your system manufacturer or retailer or learn more at intel.com.
- No license (express or implied, by estoppel or otherwise) to any intellectual property rights is granted by this document.
- Intel disclaims all express and implied warranties, including without limitation, the implied warranties of merchantability, fitness for a particular purpose, and non-infringement, as well as any warranty arising from course of performance, course of dealing, or usage in trade.
- Intel, the Intel logo, Intel Core, Intel Optane, Intel 3D XPoint, Intel Performance Maximizer, and Thunderbolt are trademarks of Intel Corporation or its subsidiaries in the U.S. and/or other countries.
- © Intel Corporation 2019.
- *Other names and brands may be claimed as the property of others.



“ Ideally one would desire an **indefinitely large memory capacity** such that any particular … word would be **immediately available**. … It **does not seem possible physically** to achieve such a capacity. We are therefore forced to recognize the possibility of **constructing a hierarchy of memories**, each of which has **greater capacity than the preceding** but which is **less quickly accessible**.”

Preliminary Discussion of the Logical Design of an Electronic Computing Instrument
Arthur Burks, Herman Goldstine and John von Neumann, 1946

MEMORY AND STORAGE HIERARCHY

MEMORY

STORAGE

1000X

100X

1 DIMM:
10s GB
<100ns

1 SSD:
10s TB
<100µsecs

1 HDD:
10s TB
<10 msecs

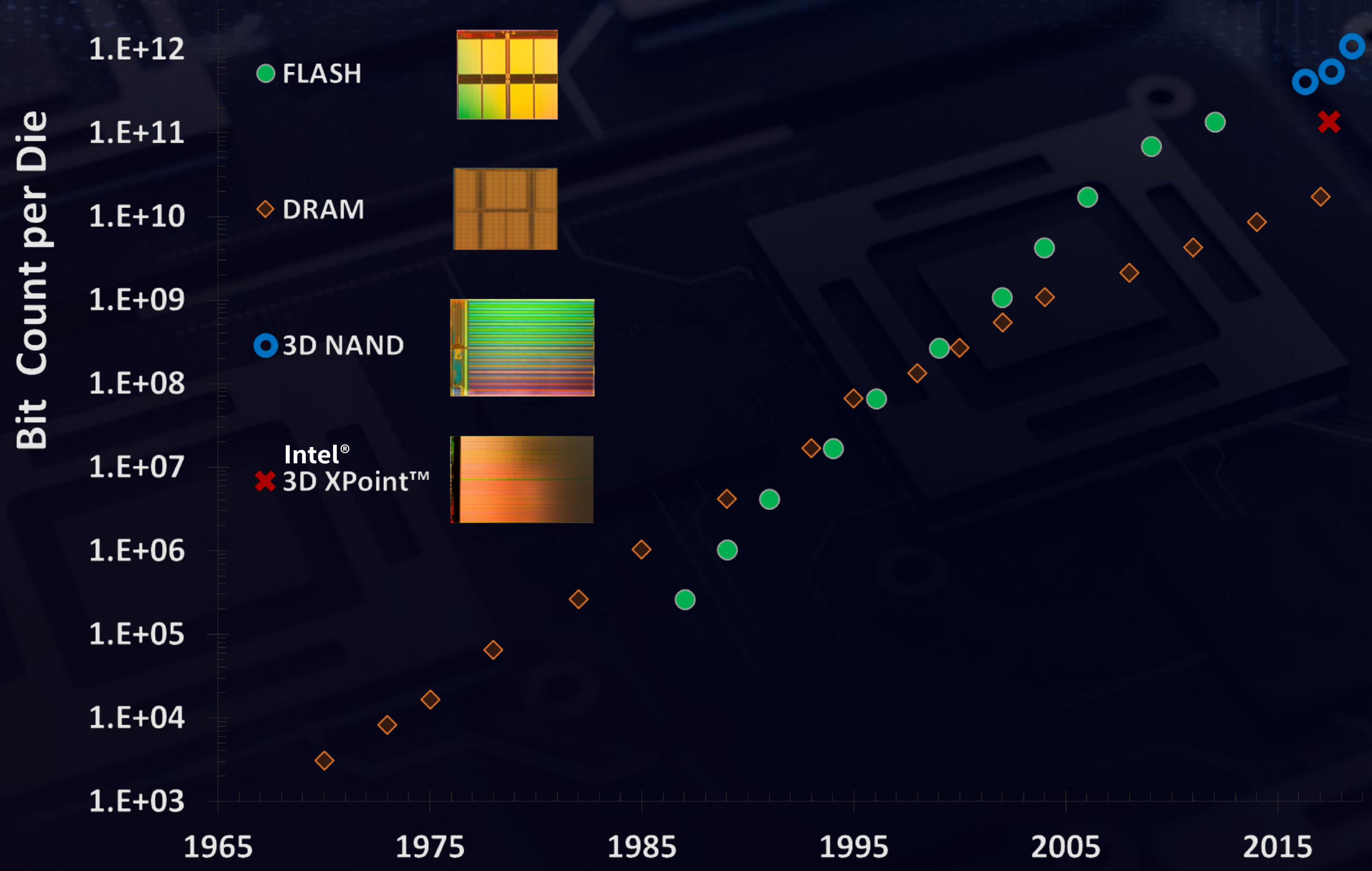
90/10 LOCALITY "RULE"

10X CAPACITY

1/10TH PERFORMANCE

- 10x performance

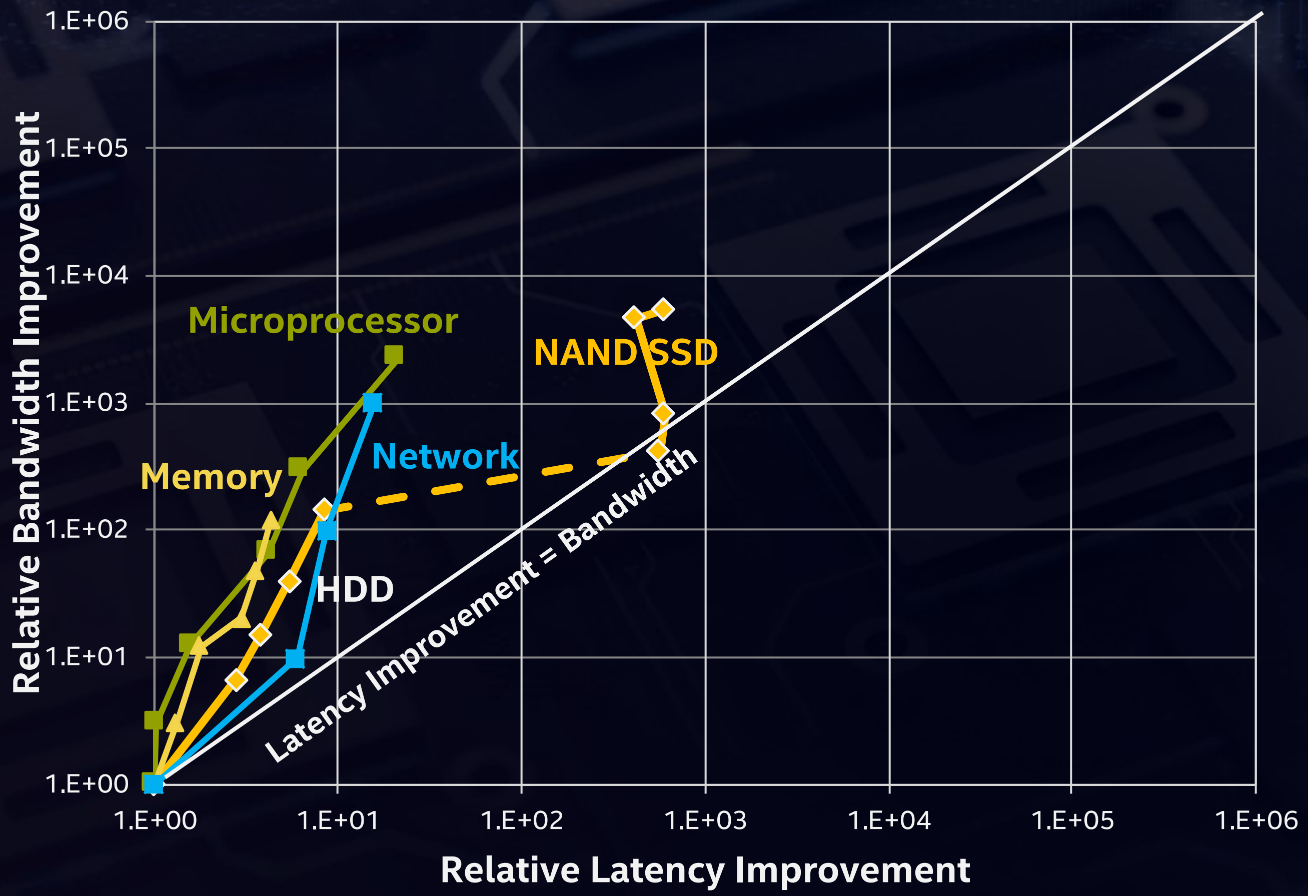
CAPACITY : TECHNOLOGY SCALING



DRAM SCALING SLOWED, NAND SCALING KEPT PACE

Source: Intel: Presented at IEEE S3S (SOI-3D-SUBTHRESHOLD) in 2017

PERFORMANCE: TECHNOLOGY SCALING



Source: "Latency lags Bandwidth" – David Patterson Comms. of the ACM, Oct 2004 Vol 47, No 10

NAND SSD data points added by Intel Based on product brief specifications for Intel NAND SSDs available at www.intel.com

CONCLUSIONS: EVOLUTIONARY IMPROVEMENTS DELIVER IMPROVED BANDWIDTH
ONLY NEW TECHNOLOGIES CAN DELIVER IMPROVED LATENCY

MEMORY AND STORAGE HIERARCHY GAPS

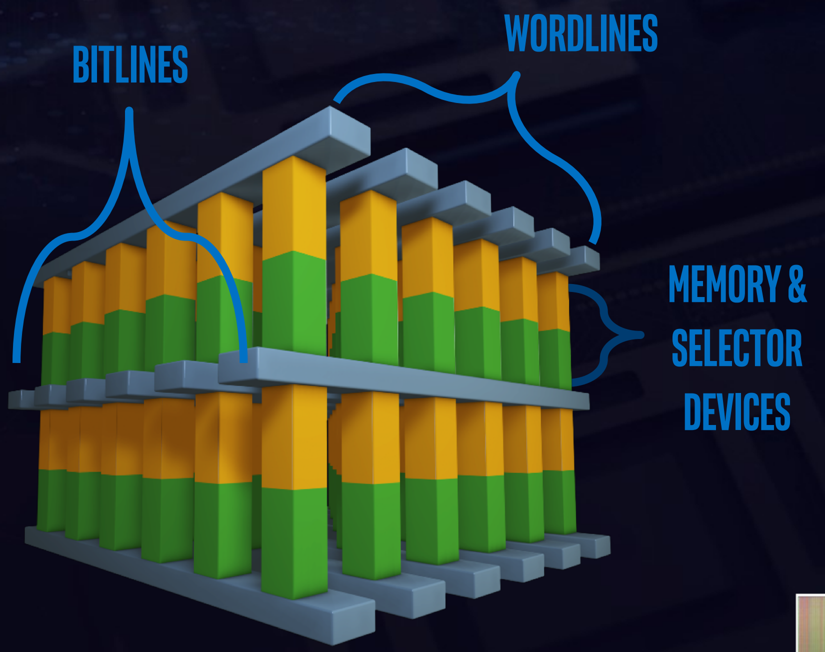
10s GB
<100ns

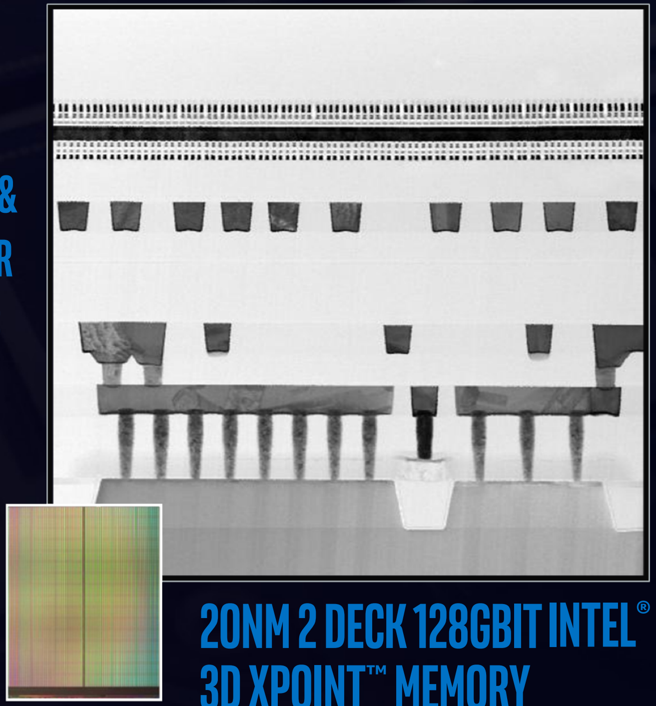
10s TB
<100µsecs

10s TB
<10 msecs

SOLUTION MUST MEET:
- CAPACITY
- SYSTEM PERFORMANCE
- SYSTEM FIT

A CONVERGENT MEMORY



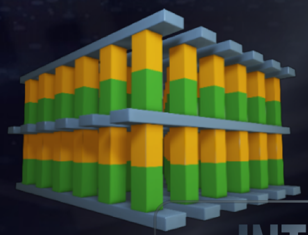


20NM 2 DECK 128GBIT INTEL®
3D XPOINT™ MEMORY

Desirable Attributes: Non-volatile, Low Cost, High Performance

- Memory in atomistic state, not electrostatic
  → **Non-Volatile** and Scalable
- Simple scalable structure + 3D technology
  → **Large Memory Capacity**
- Fast switching materials + local low resistance metal interconnect
  → **Immediately Available**
- Individual Cell Access
  → **Word Access**

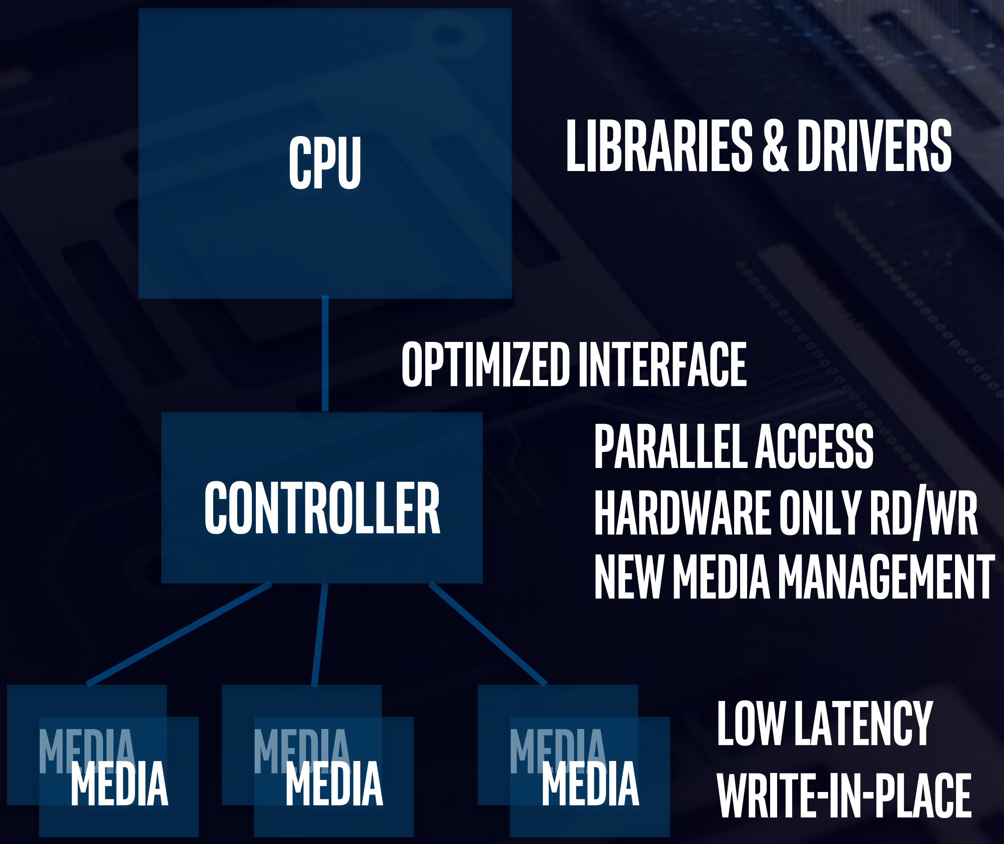
INTEL® OPTANE™ TECHNOLOGY: BUILDING BLOCKS



INTEL MEMORY AND STORAGE CONTROLLERS

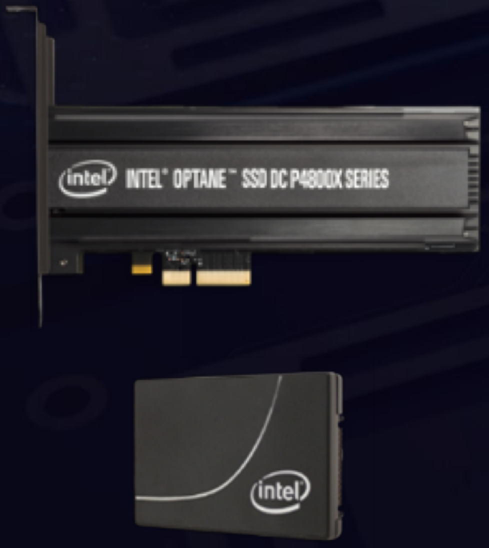
\+ INTEL INTERCONNECT IP

\+ INTEL® SOFTWARE

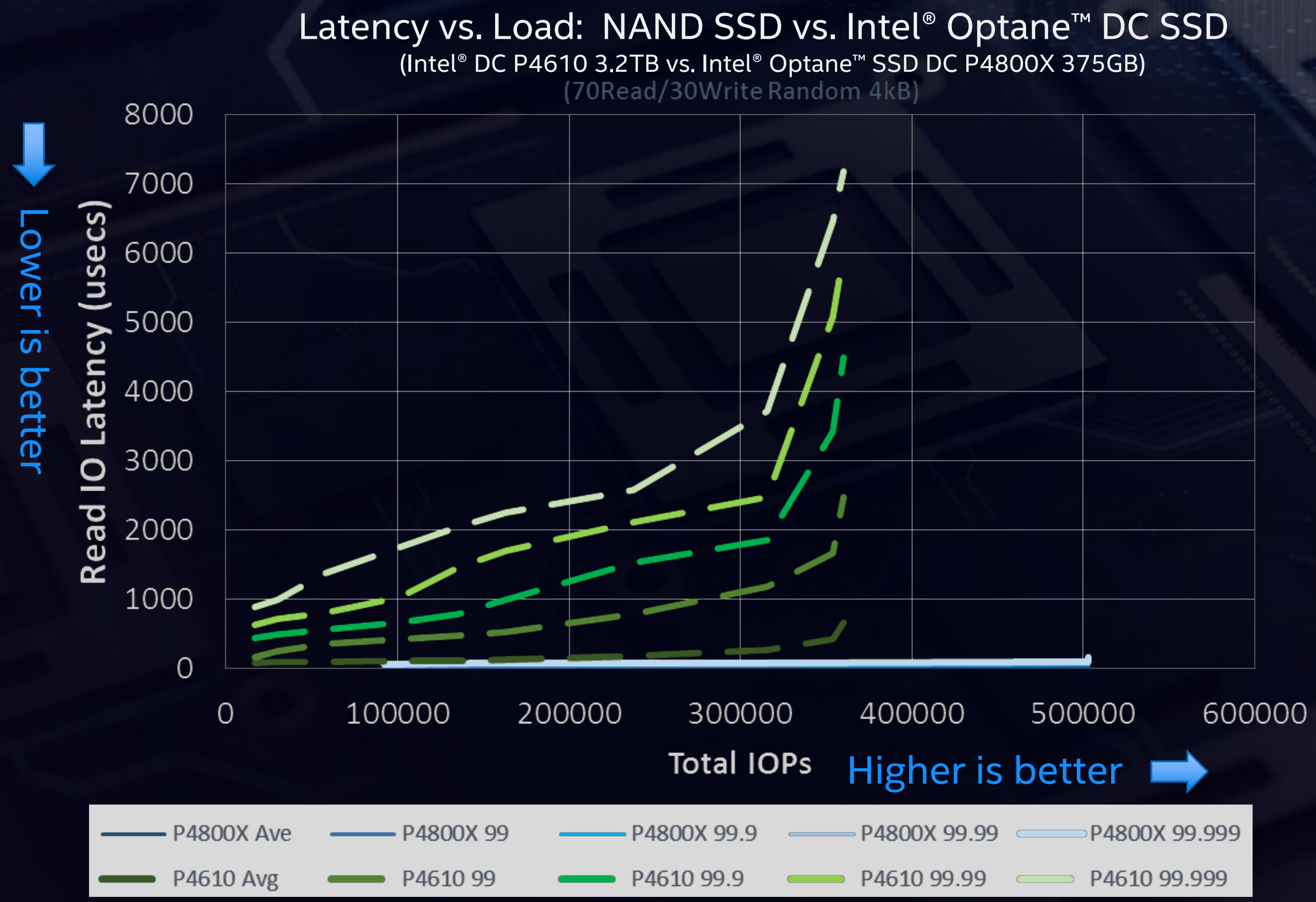


PLATFORM LEVEL INNOVATION ENABLES SYSTEM FIT

INTEL® OPTANE™ SSD



SYSTEM FIT

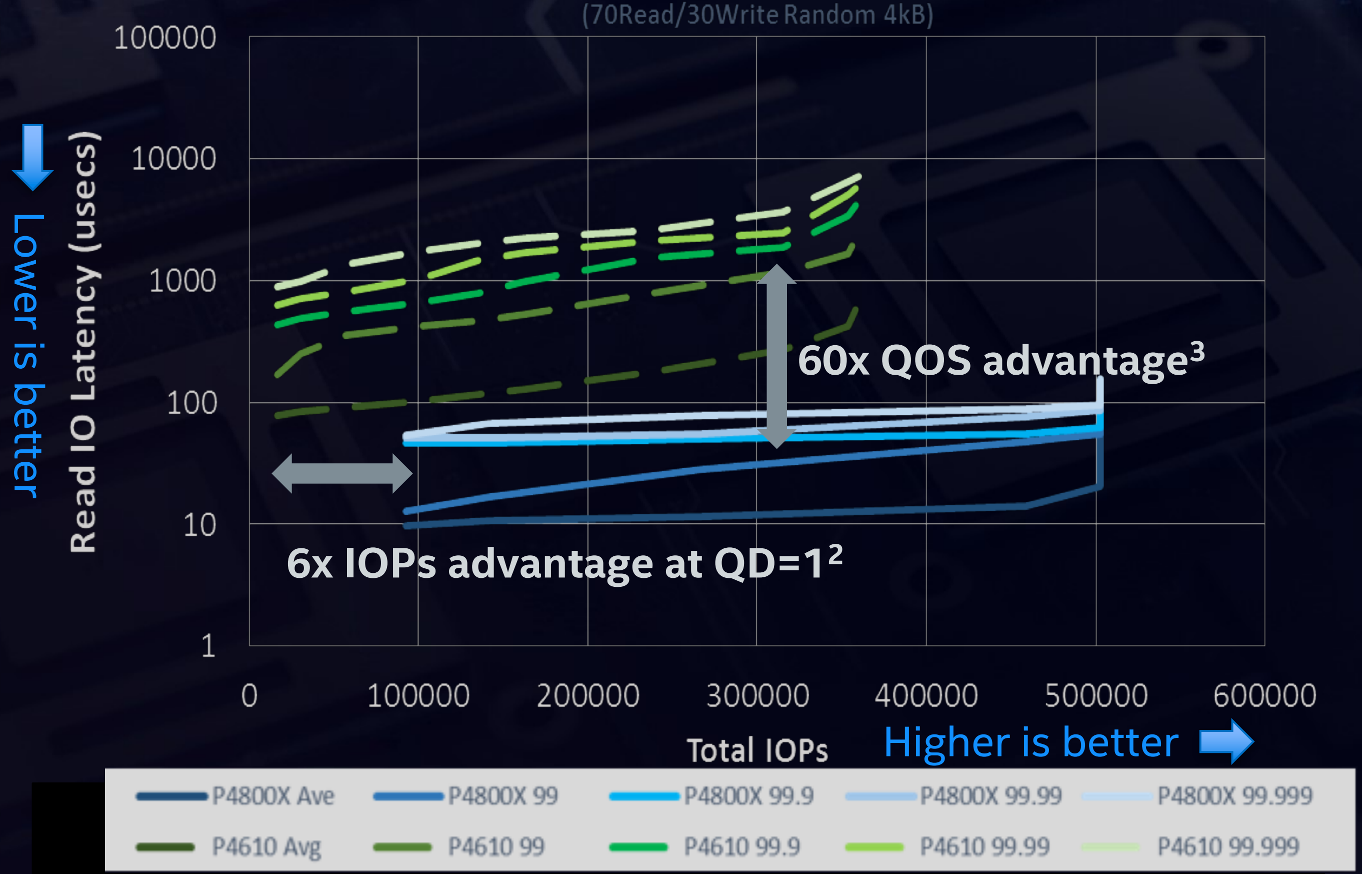


Software and workloads used in performance tests may have been optimized for performance only on Intel microprocessors. Performance tests, such as SYSmark and MobileMark, are measured using specific computer systems, components, software, operations and functions. Any change to any of those factors may cause the results to vary. You should consult other information and performance tests to assist you in fully evaluating your contemplated purchases, including the performance of that product when combined with other products. For more complete information visit www.intel.com/benchmarks.
Source – Intel-tested: Measured using FIO 3.1. Common Configuration - Intel 2U Server System, OS CentOS 7.5, kernel 4.17.6-1.el7.x86_64, CPU 2 x Intel® Xeon® 6154 Gold @ 3.0GHz (18 cores), RAM 256GB DDR4 @ 2666MHz. Configuration – Intel® Optane™ SSD DC P4800X 375GB and *Intel® SSD DC P4600 1.6TB. Intel Microcode: 0x2000043; System BIOS: 00.01.0013; ME Firmware: 04.00.04.294; BMC Firmware: 1.43.91f76955; FRUSDR: 1.43. The benchmark results may need to be revised as additional testing is conducted. Performance results are based on testing as of November 15, 2018 and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure.

SYSTEM LEVEL PERFORMANCE

Latency vs. Load: NAND SSD vs. Intel® Optane™ DC SSD [1]

(Intel® DC P4610 3.2TB vs. Intel® Optane™ SSD DC P4800x 375GB)



[1] Software and workloads used in performance tests may have been optimized for performance only on Intel microprocessors. Performance tests, such as SYSmark and MobileMark, are measured using specific computer systems, components, software, operations and functions. Any change to any of those factors may cause the results to vary. You should consult other information and performance tests to assist you in fully evaluating your contemplated purchases, including the performance of that product when combined with other products. For more complete information visit www.intel.com/benchmarks.

Source – Intel-tested: Measured using FIO 3.1. Common Configuration - Intel 2U Server System, OS CentOS 7.5, kernel 4.17.6-1.el7.x86_64, CPU 2 x Intel® Xeon® 6154 Gold @ 3.0GHz (18 cores), RAM 256GB DDR4 @ 2666MHz. Configuration – Intel® Optane™ SSD DC P4800X 375GB and *Intel® SSD DC P4600 1.6TB. Intel Microcode: 0x2000043; System BIOS: 00.01.0013; ME Firmware: 04.00.04.294; BMC Firmware: 1.43.91f76955; FRUSDR: 1.43. The benchmark results may need to be revised as additional testing is conducted. Performance results are based on testing as of November 15, 2018 and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure.

2Source – Intel-tested: 4K 70/30 RW Performance at Low Queue Depth. Test and System Configuration: CPU: Xeon Skylake Gold 6140 FC-LGA14B 2.3GHz 24.75MB 140W 18 cores CD8067303405200 , CPU Sockets: 2, RAM Capacity: 32G, RAM Model: DDR4, RAM Stuffing: NA, DIMM Slots Populated: 2 slots, PCIe Attach: CPU (not PCH lane attach), Chipset: Intel C620 chipset BIOS: SE5C620.86B.00.01.0013.030920180427 , Switch/ReTimer Model/Vendor: Cable - Oculink 800mm straight SFF-8611 to right angle SFF-8611 Intel AXXCBL800CVCR, OS: CentOS 7.5, Kernel: 4.14.50(LTS), FIO version: 3.5; NVMe Driver: Inbox, C-states: Disabled, Hyper Threading: Disabled, CPU Governor (through OS): Performance Mode. EIST (Speed Step), Intel Turbo Mode=Disabled, and P-states = Enabled. The benchmark results may need to be revised as additional testing is conducted. Performance results are based on testing as of July 2018 and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure

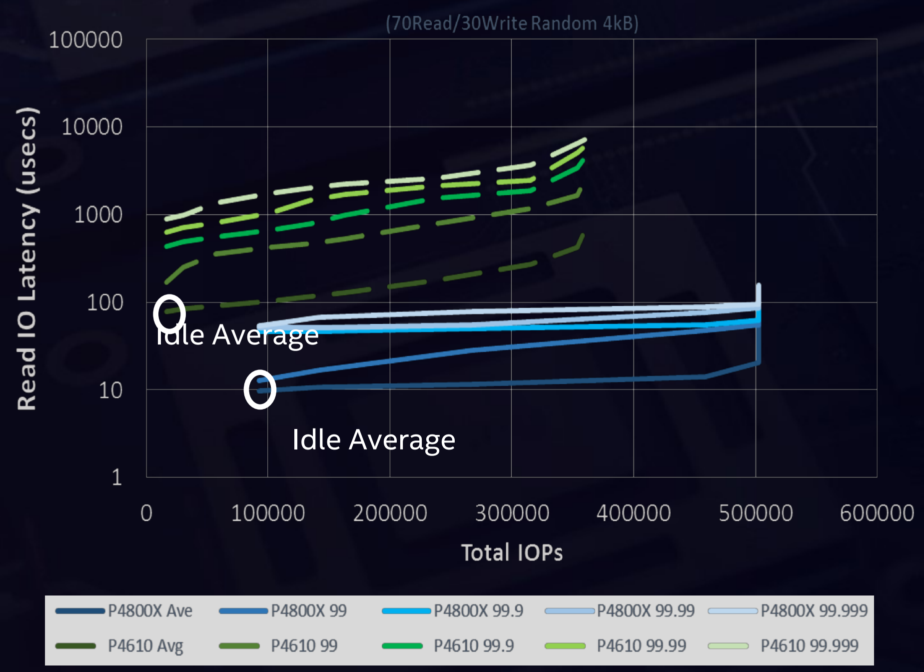
3Source – Intel-tested: 4K Read Latency under 500MB/s Write Workload. Measured using FIO 2.15. Tests document performance of components on a particular test, in specific systems. Differences in hardware, software, or configuration will affect actual performance. Consult other sources of information to evaluate performance as you consider your purchase. For more complete information about performance and benchmark results, visit www.intel.com/benchmarks. Common Configuration - Intel 2U Server System, OS CentOS 7.5, kernel 4.17.6-1.el7.x86_64, CPU 2 x Intel® Xeon® 6154 Gold @ 3.0GHz (18 cores), RAM 256GB DDR @ 2666MHz. Configuration – Intel® Optane™ SSD DC P4800X 375GB and Intel® SSD DC P4600 1.6TB. Latency – Average read latency measured at QD1 during 4K Random Write operations using fio-2.15. System BIOS: 00.01.0013; ME Firmware: 04.00.04.294; BMC Firmware: 1.43.91f76955; FRUSDR: 1.43. The benchmark results may need to be revised as additional testing is conducted. Performance results are based on testing as of July 2018 and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure

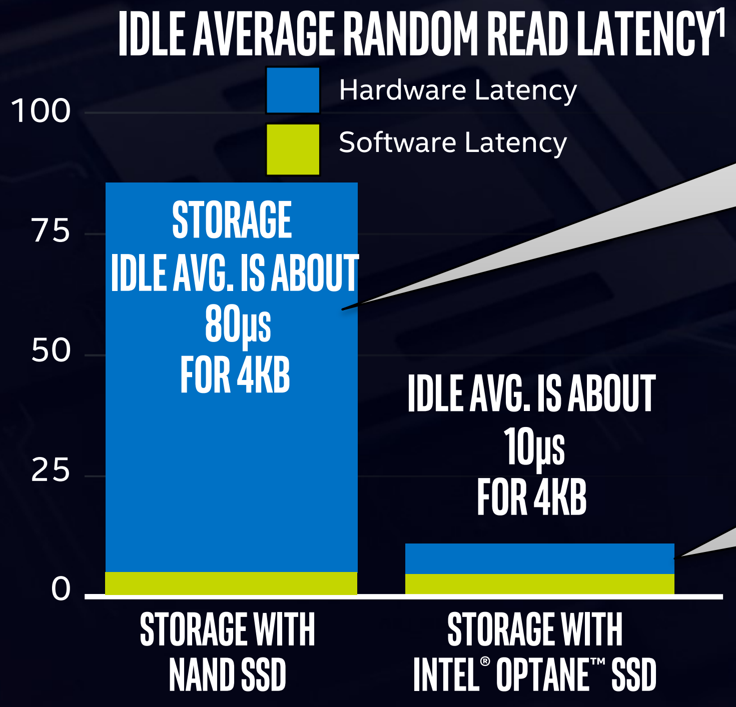
For more complete information about performance and benchmark results, visit www.intel.com/benchmarks.

LATENCY IMPROVEMENT REQUIRES SYSTEM INNOVATION

Latency vs. Load: NAND SSD vs. Intel® Optane™ SSD [2]

(Intel® DC P4610 3.2TB vs. Intel® Optane™ SSD DC P4800x 375GB)





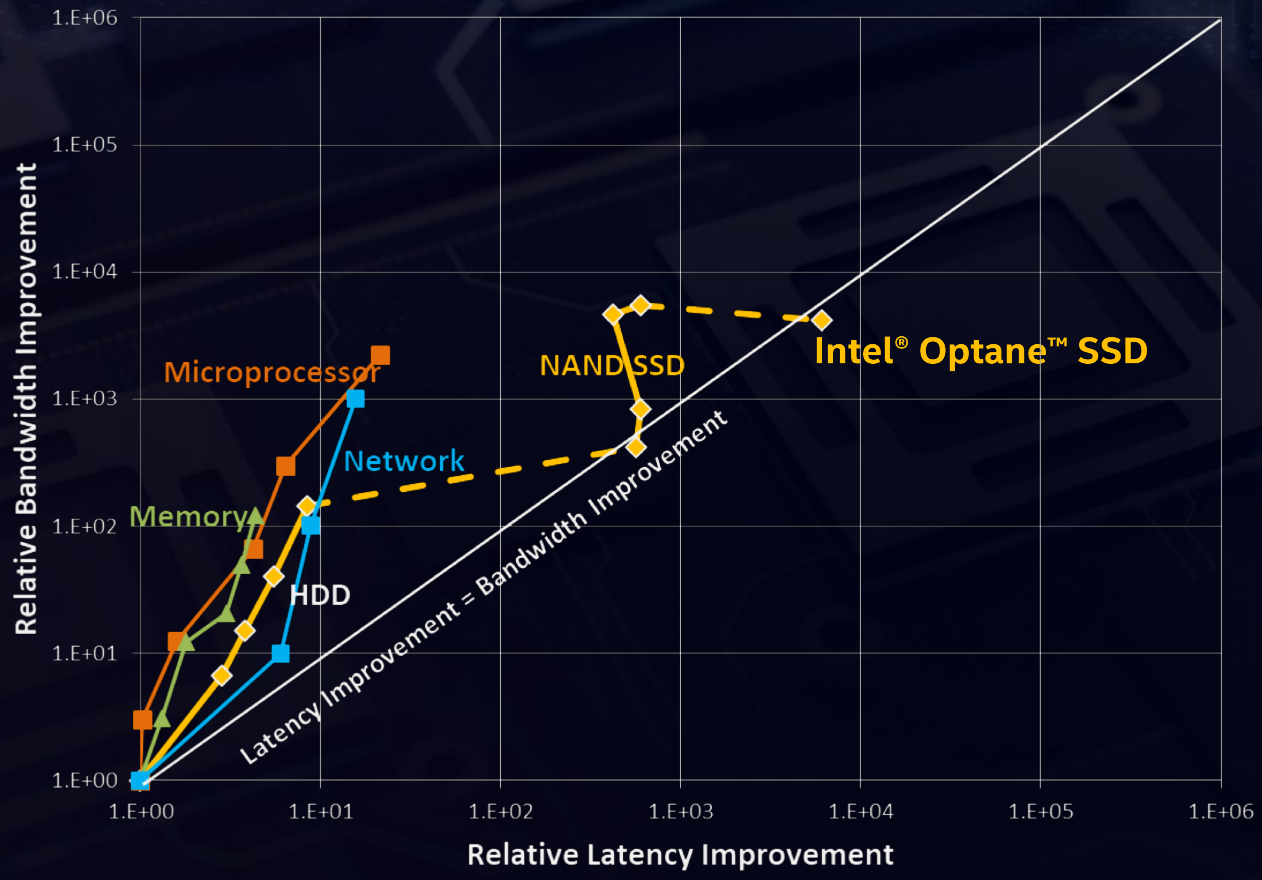
NAND SSD latency dominated by media latency

Optane SSD latency balanced between SSD and System

[1] Source – Intel-tested: Average read latency measured at queue depth 1 during 4k random write workload. Measured using FIO 3.1. Common Configuration - Intel 2U Server System, OS CentOS 7.5, kernel 4.17.6-1.el7.x86_64, CPU 2 x Intel® Xeon® 6154 Gold @ 3.0GHz (18 cores), RAM 256GB DDR4 @ 2666MHz. Configuration – Intel® Optane™ SSD DC P4800X 375GB and Intel® SSD DC P4600 1.6TB. Latency – Average read latency measured at QD1 during 4K Random Write operations using FIO 3.1. Intel Microcode: 0x2000043; System BIOS: 00.01.0013; ME Firmware: 04.00.04.294; BMC Firmware: 1.43.91f76955; FRUSDR: 1.43. SSDs tested were commercially available at time of test. The benchmark results may need to be revised as additional testing is conducted. Performance results are based on testing as of July 24, 2018 and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure. Software and workloads used in performance tests may have been optimized for performance only on Intel microprocessors. Performance tests, such as SYSmark and MobileMark, are measured using specific computer systems, components, software, operations and functions. Any change to any of those factors may cause the results to vary. You should consult other information and performance tests to assist you in fully evaluating your contemplated purchases, including the performance of that product when combined with other products. For more complete information visit www.intel.com/benchmarks.

[2] See Note on previous slide

PERFORMANCE: TECHNOLOGY SCALING



Source: "Latency lags Bandwidth" – David Patterson Comms. of the ACM, Oct 2004 Vol 47, No 10

NAND and Optane SSD data points added by Intel Based on product brief specifications for Intel NAND and Optane SSDs available at www.intel.com

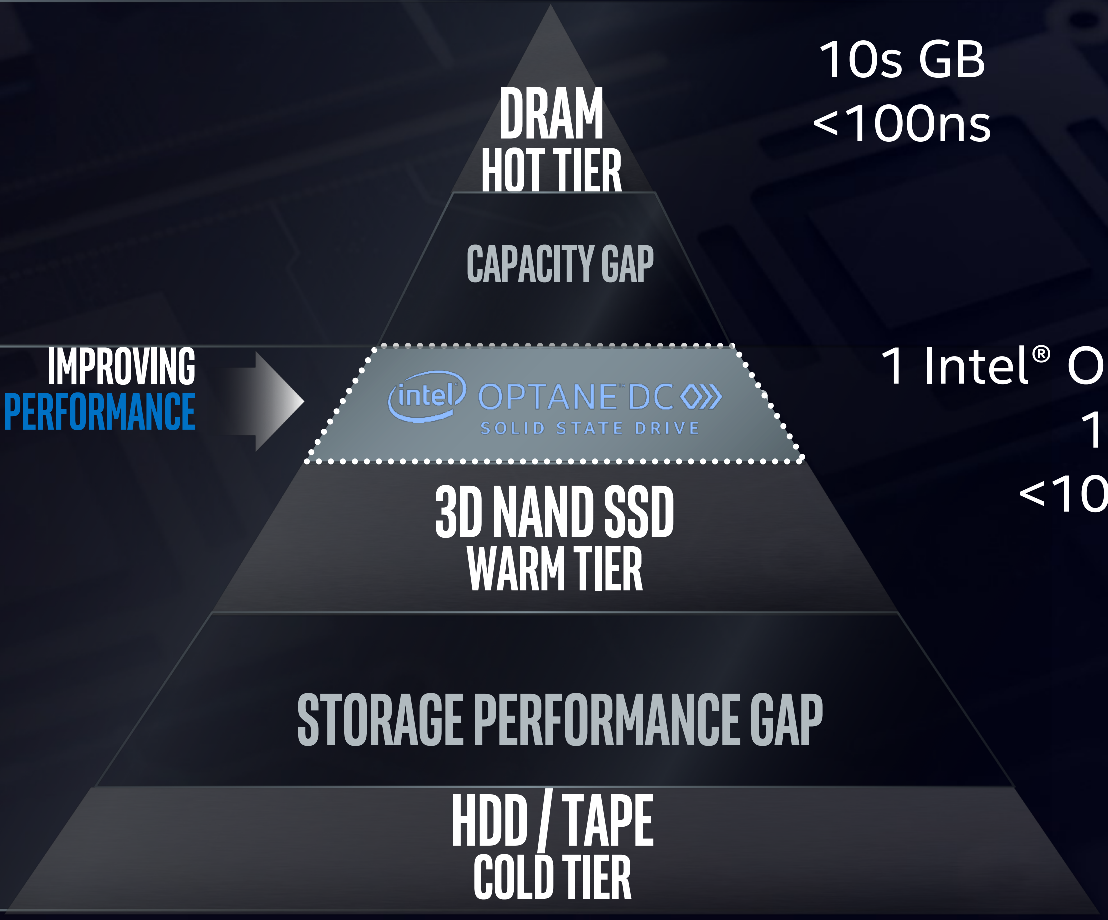
INTEL® OPTANE™ SSDS PUT STORAGE BACK IN THROUGHPUT/LATENCY BALANCE

MEMORY AND STORAGE HIERARCHY

MEMORY

STORAGE

IMPROVING
SSD PERFORMANCE



10s GB
<100ns

1 Intel® Optane™ SSD:
1sTB
<10µsecs

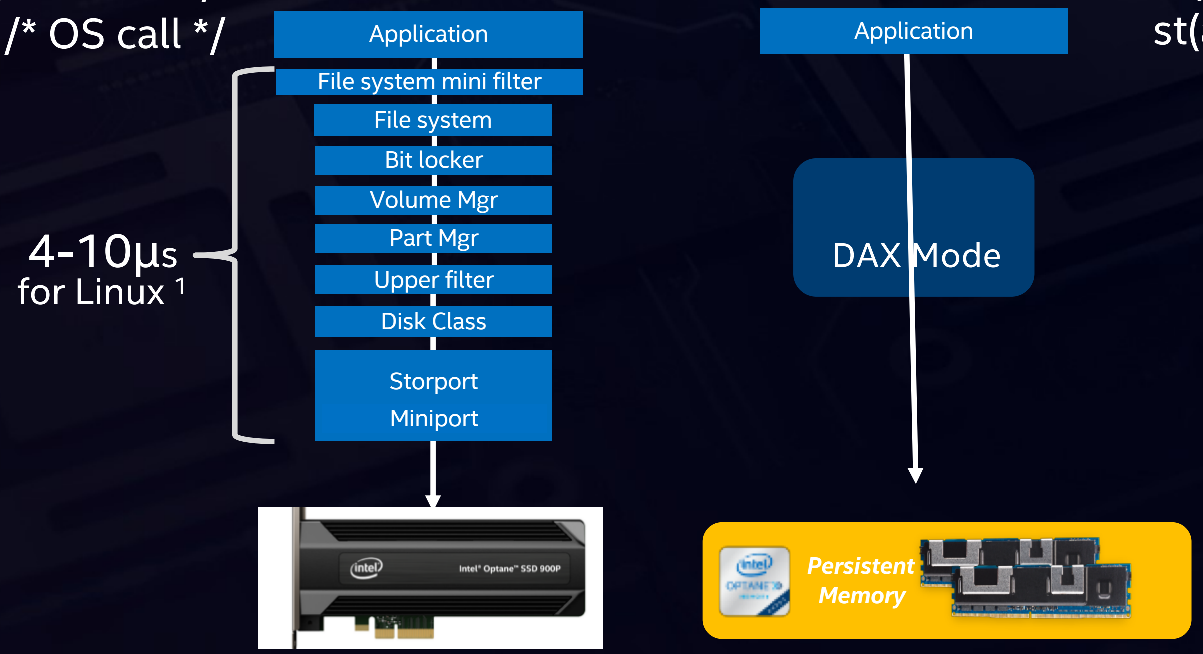
LOW LATENCY SOFTWARE PATH

STORAGE

PERSISTENT MEMORY

Read(fileptr,offset) /* OS call */
Write(fileptr,offest) /* OS call */

ld(address) /* CPU opcode */
st(address) /* CPU opcode */



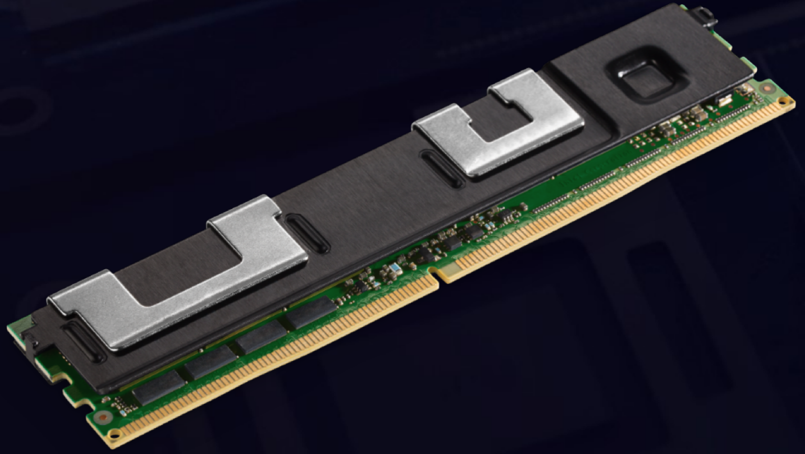
Intel® Optane™ SSD

Intel® Optane™ DC Persistent Memory

1. Platform Storage Performance With 3D Xpoint Technology. Frank Hady, Annie Foong, Bryan Veal, Dan Williams, Proceedings of the IEEE. Vol 105, No. 9, Sept 2017 http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8003284
Towards SSD-Read Enterprise Platforms. Annie Foong, Bryan Veal, Frank Hady. ASMS 2010 – First International Workshop on Accelerating Data Management Systems Using Modern Processor and Storage Architecture. http://www.vldb2010.org/proceedings/files/vldb_2010_workshop/ADMS_2010/adms10-foong.pdf September 2010

PERSISTENT MEMORY PLATFORM SUPPORT

intel OPTANE DC
PERSISTENT MEMORY



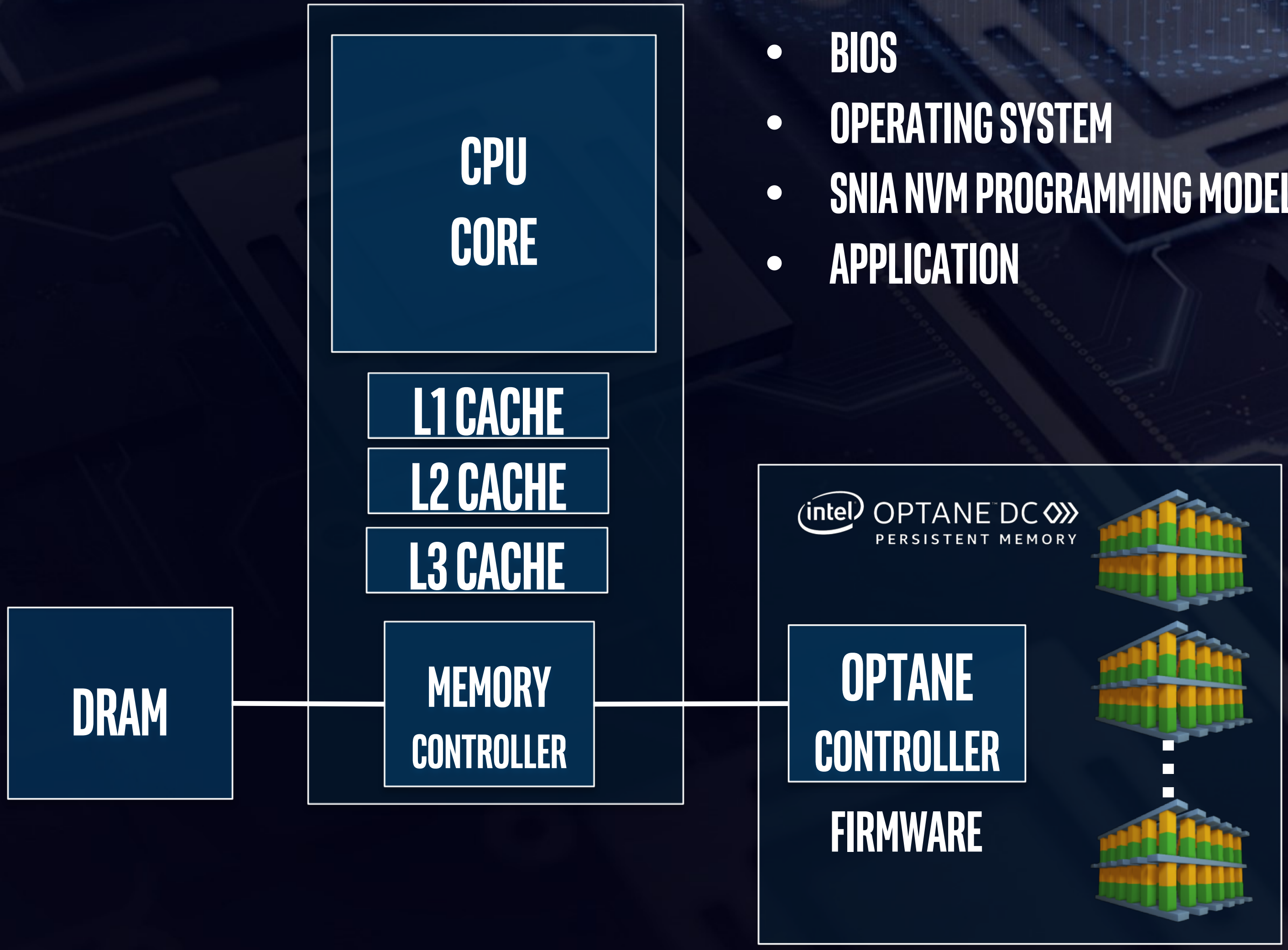
Direct Load/Store Access

Native Persistence

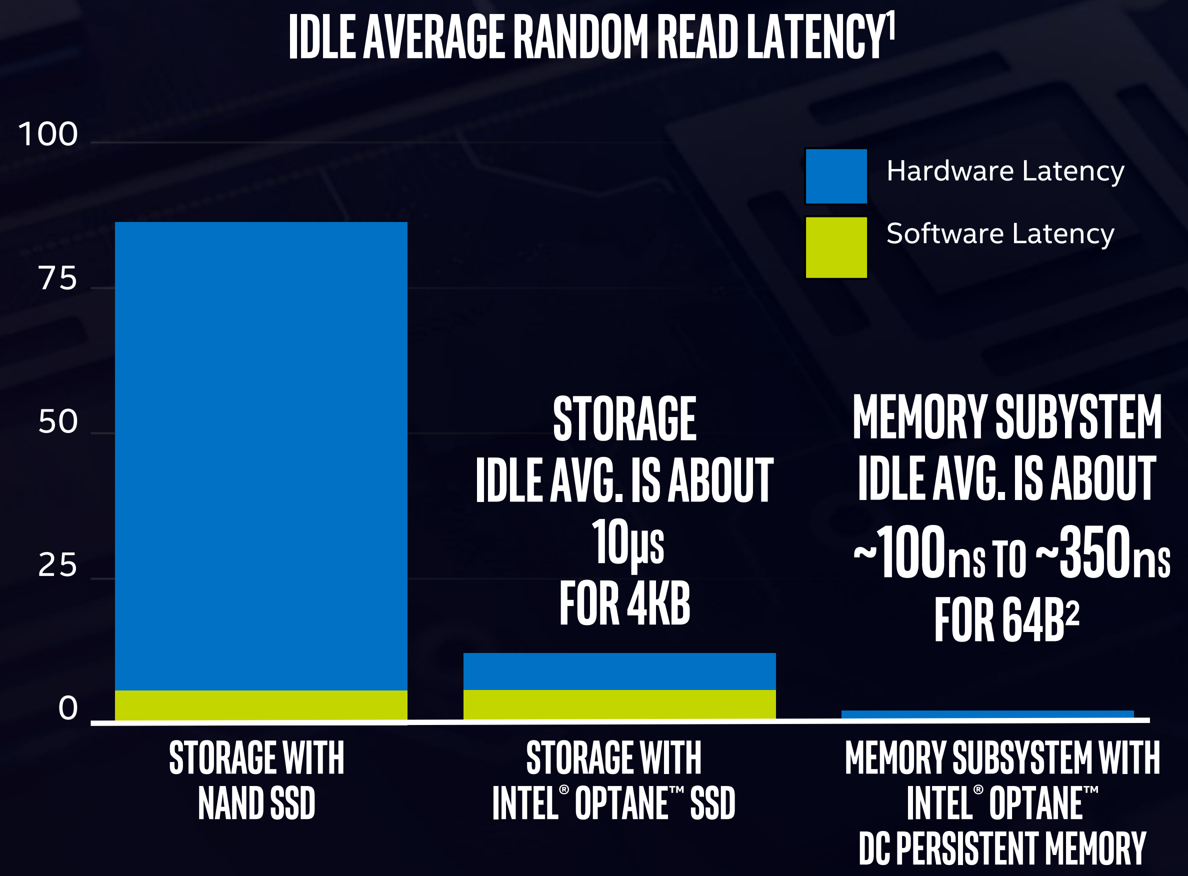
128, 256, 512GB

DDR4 Pin Compatible

- BIOS
- OPERATING SYSTEM
- SNIA NVM PROGRAMMING MODEL
- APPLICATION



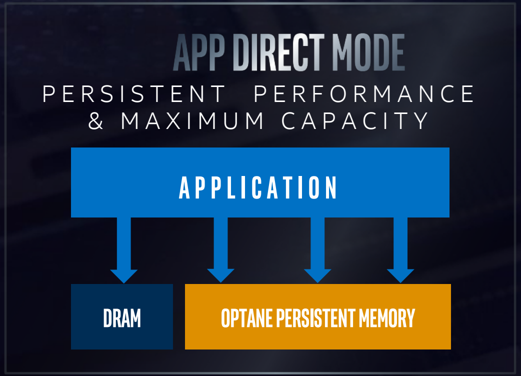
LOW LATENCY SYSTEM ACCESS TO PERSISTENT MEMORY



[1] Source: Intel-tested: Average read latency measured at queue depth 1 during 4k random write workload. Measured using FIO 3.1. comparing Intel Reference platform with Optane™ SSD DC P4800X 375GB and Intel® SSD DC P4600 1.6TB compared to SSDs commercially available as of July 1, 2018. Performance results are based on testing as of July 24, 2018 and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure. For more complete information about performance and benchmark results, visit www.intel.com/benchmarks.

[2] App Direct Mode , NeonCity, LBG B1 chipset , CLX B0 28 Core (QDF QQYZ), Memory Conf 192GB DDR4 (per socket) DDR 2666 MT/s, Optane DCPMM 128GB, BIOS 561.D09, BKC version WW48.5 BKC, Linux OS 4.18.8-100.fc27, Spectre/Meltdown Patched (1,2,3, 3a)

INTEL® OPTANE™ PERSISTENT MEMORY : APP DIRECT

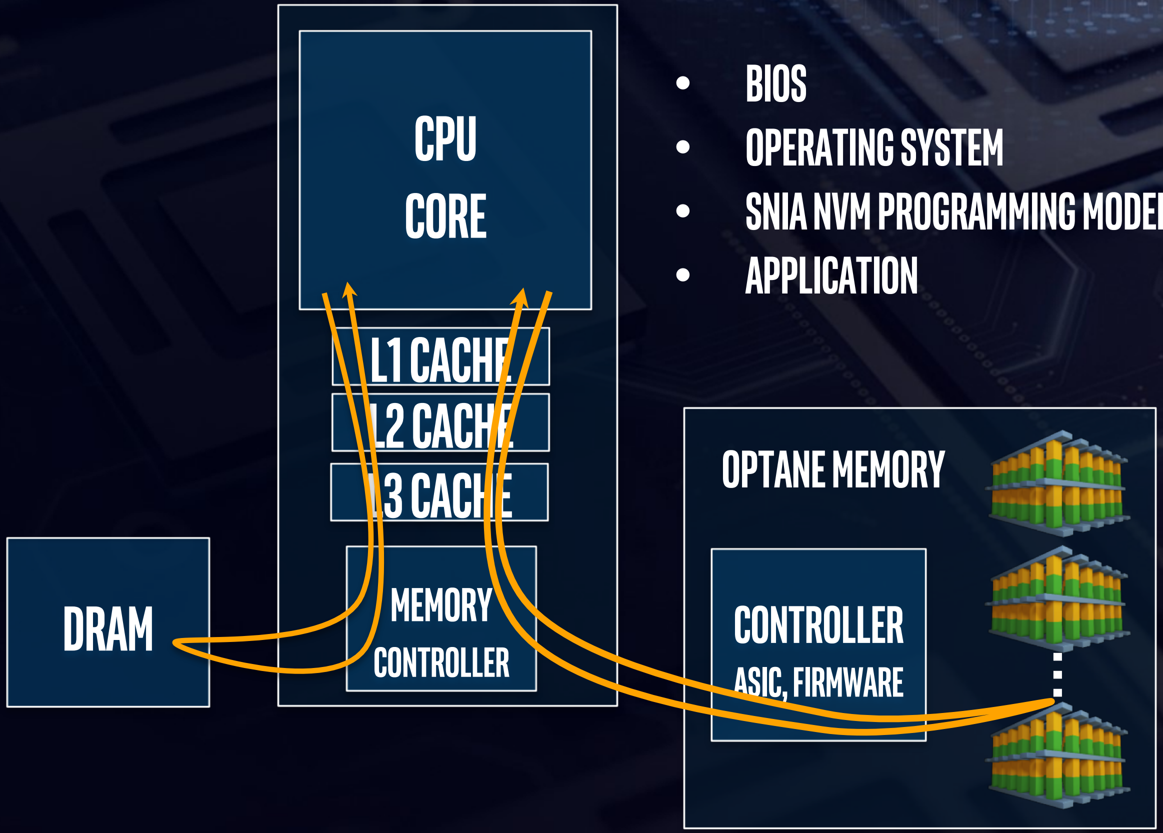


App Direct Mode provides the persistent memory programming model

- Reported to OS by ACPI
- Linux and Windows expose via ”DAX” file systems

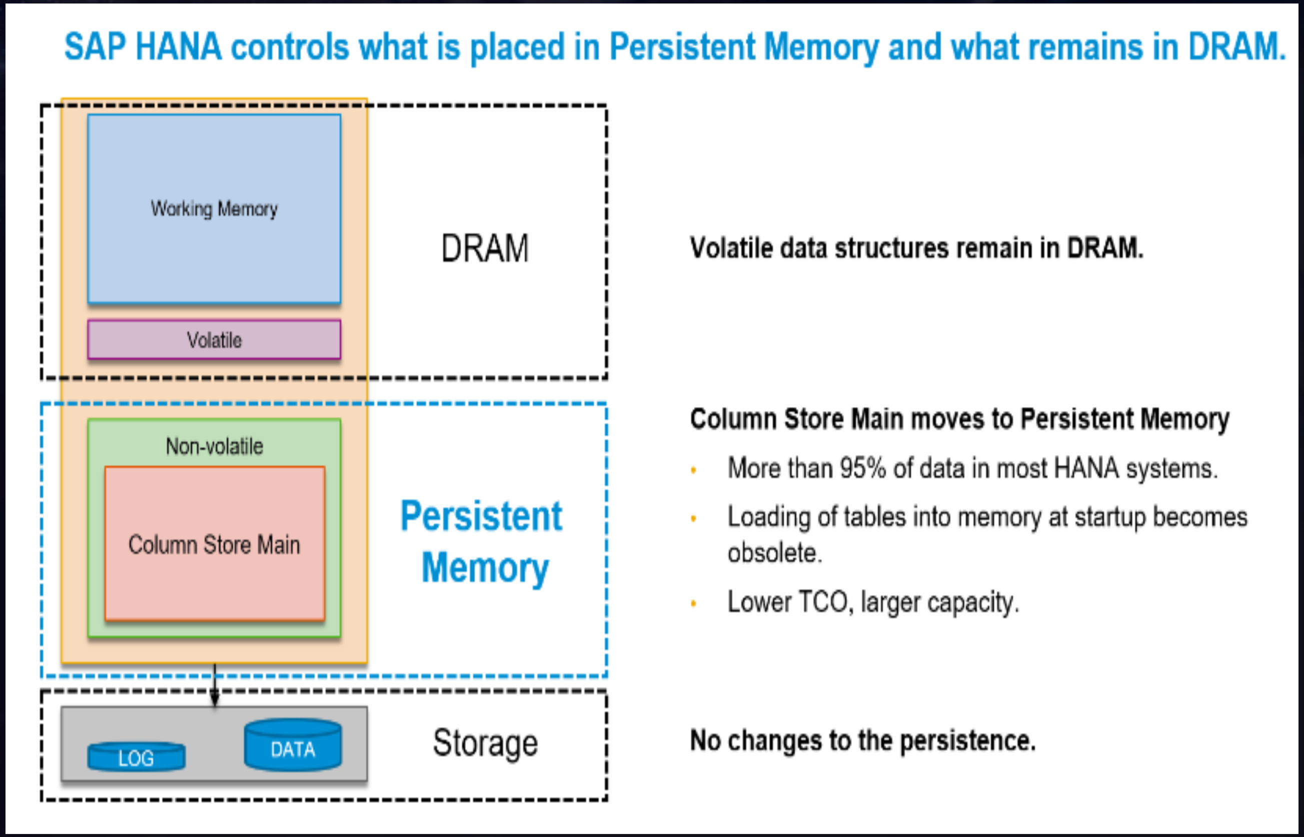
Several use cases supported by OS & PMDK APIs

- Persistent memory, non-paged (no DRAM footprint when accessed)
- Volatile App Direct, an explicit pool of volatile memory
- Storage over App Direct, a very fast SSD built on persistent memory



- BIOS
- OPERATING SYSTEM
- SNIA NVM PROGRAMMING MODEL
- APPLICATION

APP DIRECT USAGE EXAMPLE



Developer placed data structures

"SAP HANA knows which data structures benefit most from persistent memory. SAP HANA automatically detects persistent memory hardware and adjusts itself by automatically placing these data structures on persistent memory, while all others remain in DRAM"

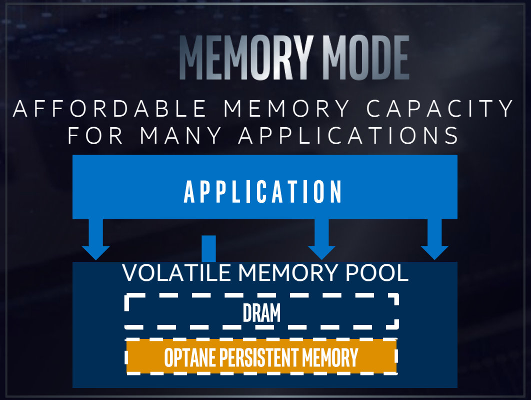
- Column Store Main in Persistent Memory
  - 90% of the data footprint
  - Nonvolatile – no initial load time
- High perf, volatile in DRAM
- SSDs still used for row store, column delta, replication, backups…

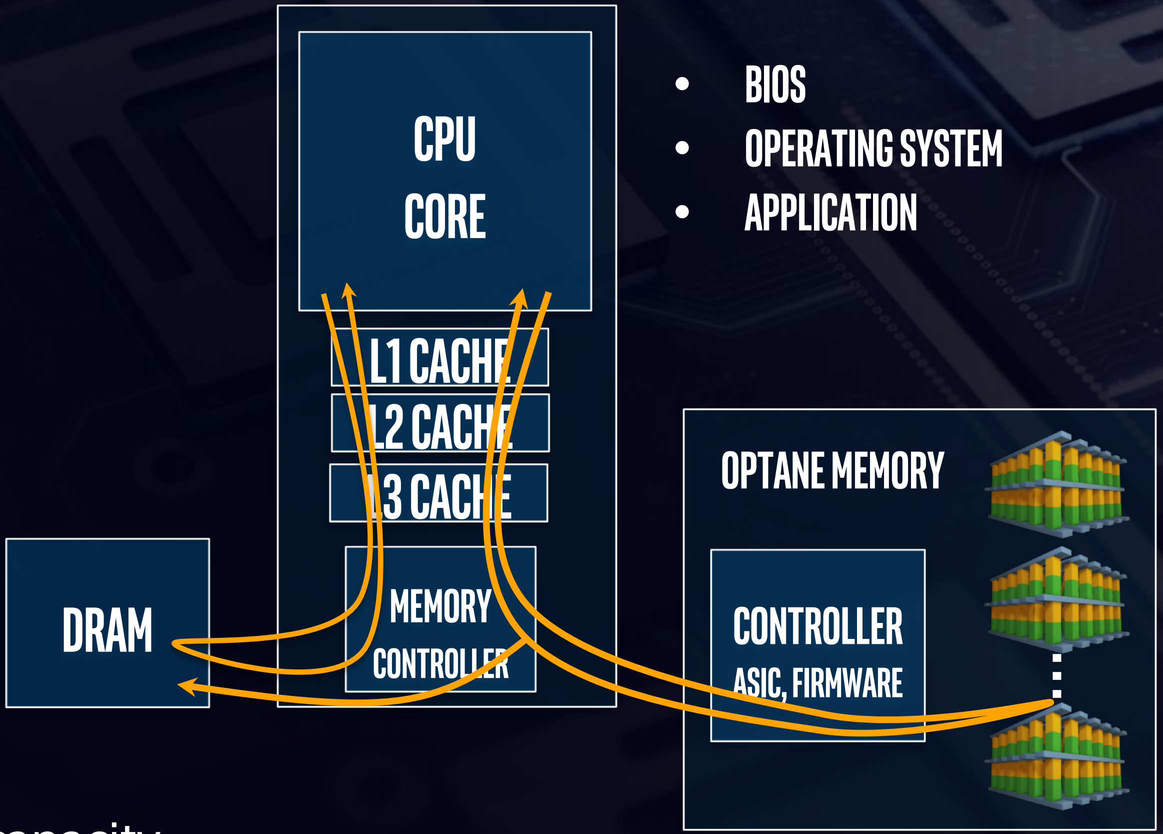
Source: "SAP HANA & Persistent Memory"
- Andreas Schuster

Dec 3 2018, https://blogs.sap.com/2018/12/03/sap-hana-persistent-memory/

[2] App Direct Mode , NeonCity, LBG B1 chipset , CLX B0 28 Core (QDF QQYZ), Memory Conf 192GB DDR4 (per socket) DDR 2666 MT/s, Intel® Optane Data Center Persistent Memory 128GB, BIOS 561.D09, BKC version WW48.5 BKC, Linux OS 4.18.8-100.fc27, Spectre/Meltdown Patched (1,2,3, 3a)

INTEL® OPTANE™ PERSISTENT MEMORY : MEMORY MODE





- BIOS
- OPERATING SYSTEM
- APPLICATION

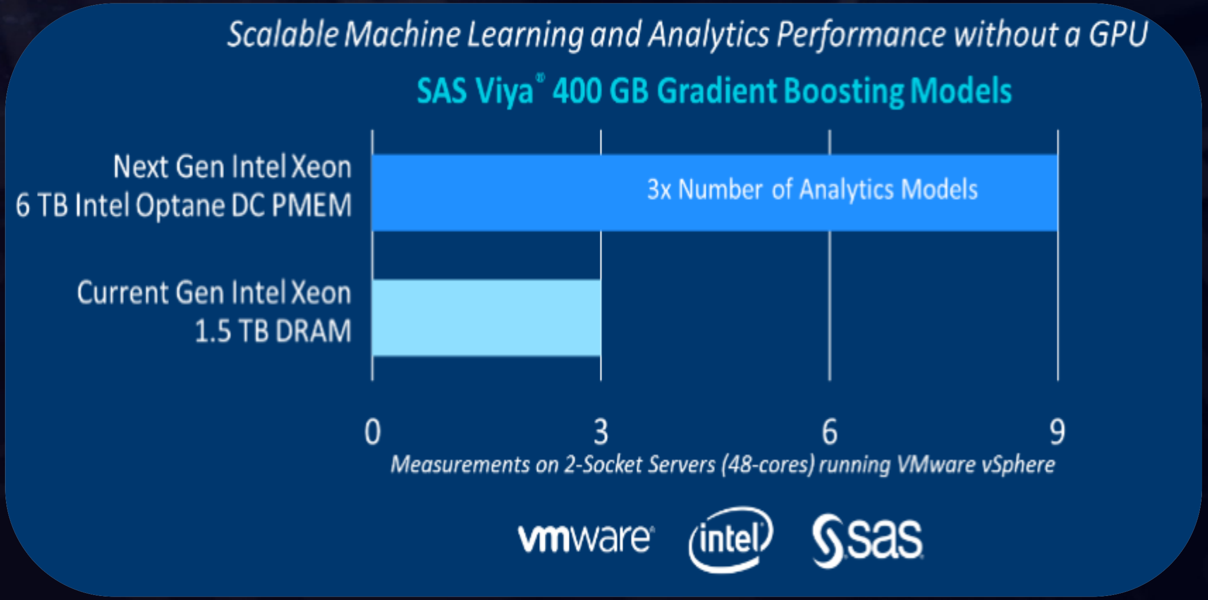
Memory Mode provides familiar volatile memory programming model

- Additional layer of caching: DRAM as WB cache
- Hardware managed, software sees very high capacity memory (6 TB)

Range of use cases supported

- No software change – big memory
- Applications/Algorithms changes for new hierarchy/capacity

MEMORY MODE USAGE EXAMPLE



Source: "Extending Memory Capacity with VMware vSphere and Upcoming Intel Optane Memory Technology" – Rich Brunner

Nov 6 2018, https://octo.vmware.com/vmware-and-intel-optane-dc-pmem/

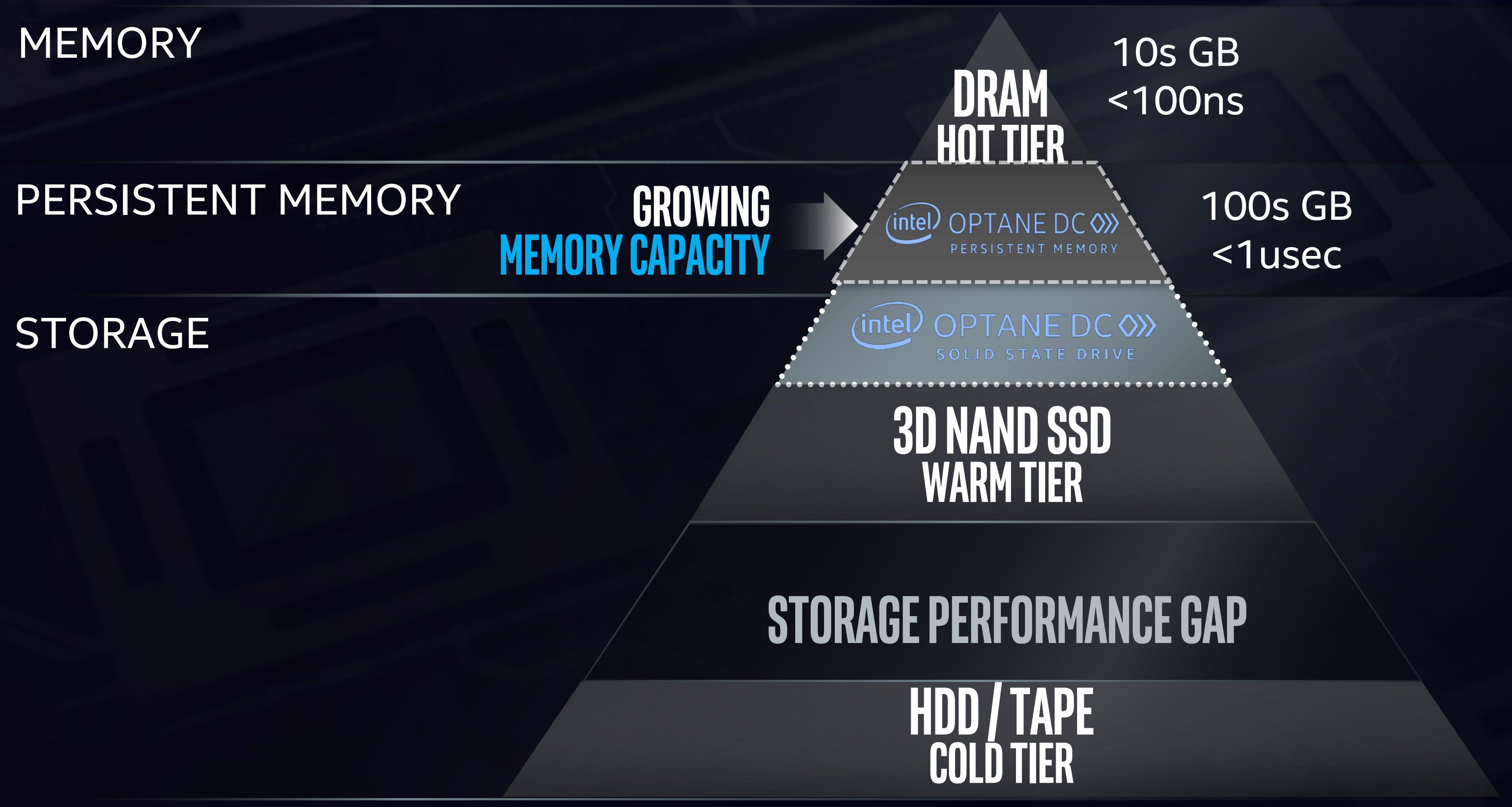
VMware vSphere* using memory mode:

"When used in memory mode, the new Intel memory technology can greatly increase the memory capacity available to software in a platform when compared with the capacity of DRAM. This increase in capacity requires no changes to your existing software, operating systems, or virtual machines."

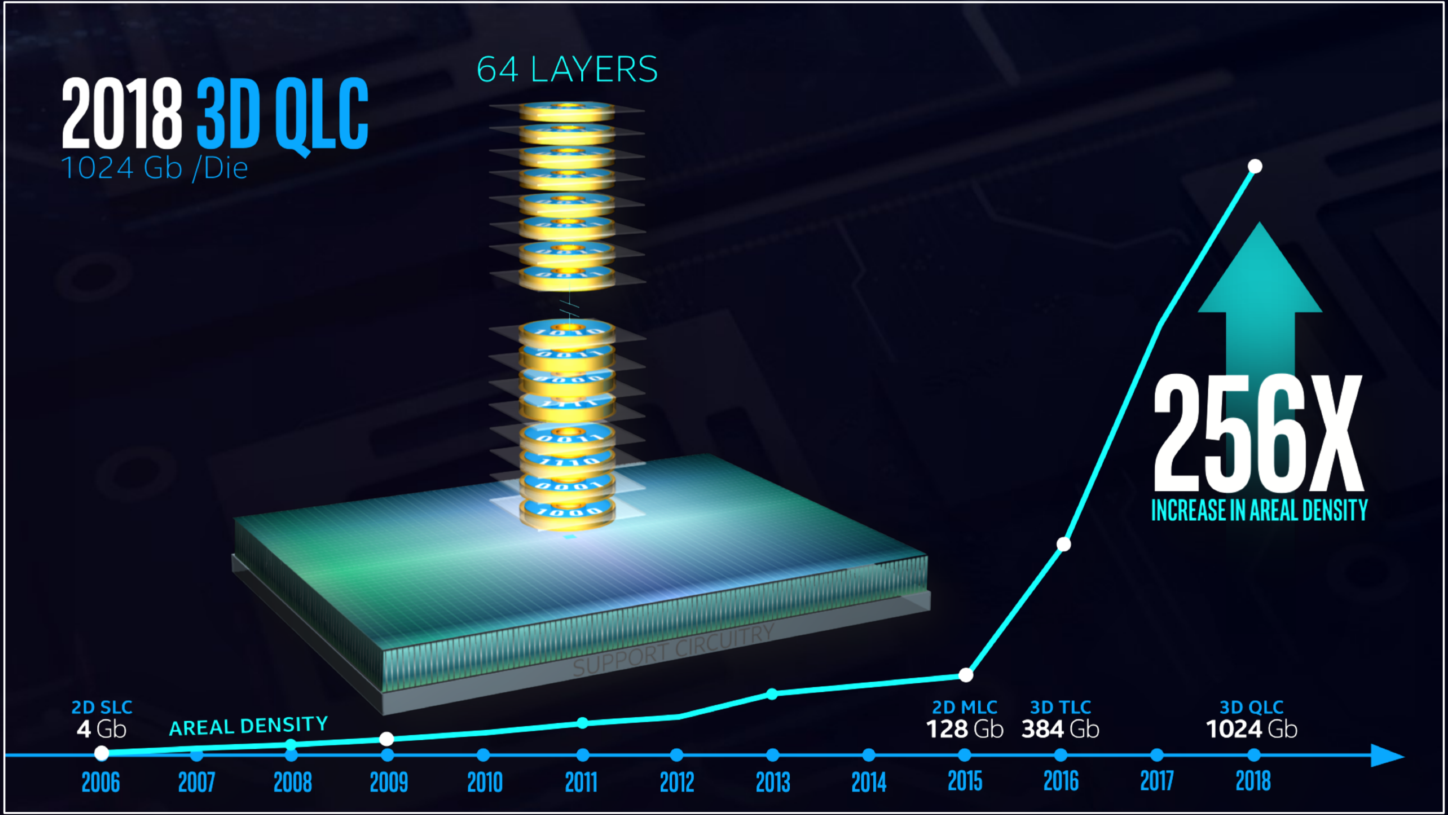
- Developer allocates VM memory images in "memory"
- Platform memory controller caches active VM data in DRAM for use

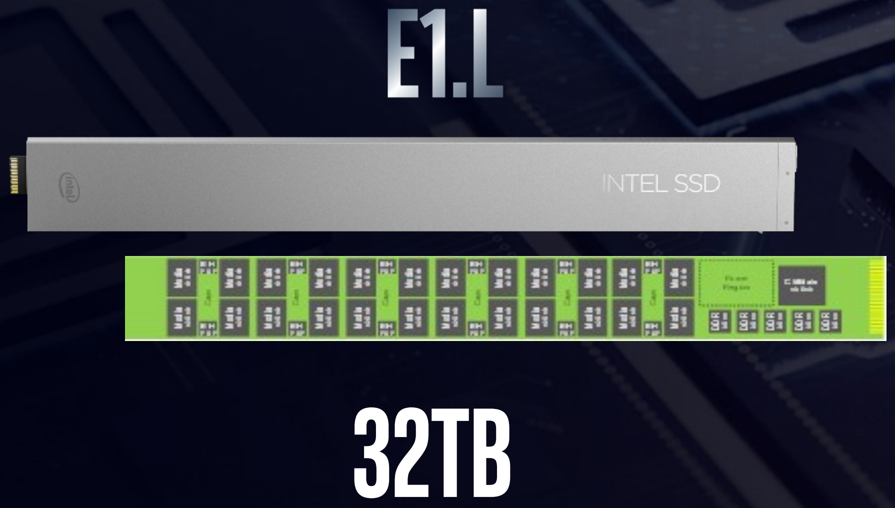
Performance results have been estimated based on SAS internal tests as of 11/05/2018 using future version of VMware vSphere, SAS Viya 400GB Gradient Boosting Models running Linux with Intel® Optane™ DC persistent memory vs. DRAM-based server and may not reflect all publicly available security updates. As measured by VMWARE on system listed as 2-CPU socket server, Intel® Cascade lake, future version of Vmware cSphere, 6TB Intel® Optane™ DC Persistent Memory in Memory Mode, versus 2-CPU socket server, Intel® Cascade lake, future version of Vmware cSphere, 1.5TB DDR4 DRAM 3x 3.6 TB SSD. Performance results are based on testing as of [INSERT DATE] and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure. For more complete information about performance and benchmark results, visit www.intel.com/benchmarks..

COMPLETE IN PERFORMANCE, CAPACITY, FIT



NAND TECHNOLOGY ADVANCEMENT

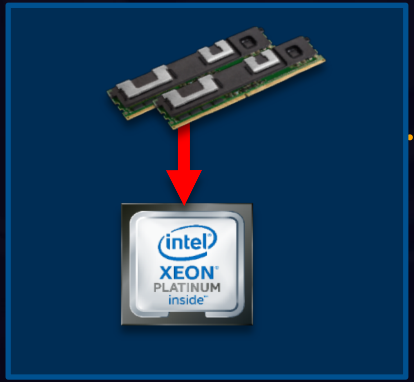




THE FUTURE OF DATA CENTER STORAGE & MEMORY

DATA/METATDATA CACHE IN PM

w/INTEL® OPTANE™ DC PERSISTENT MEMORY

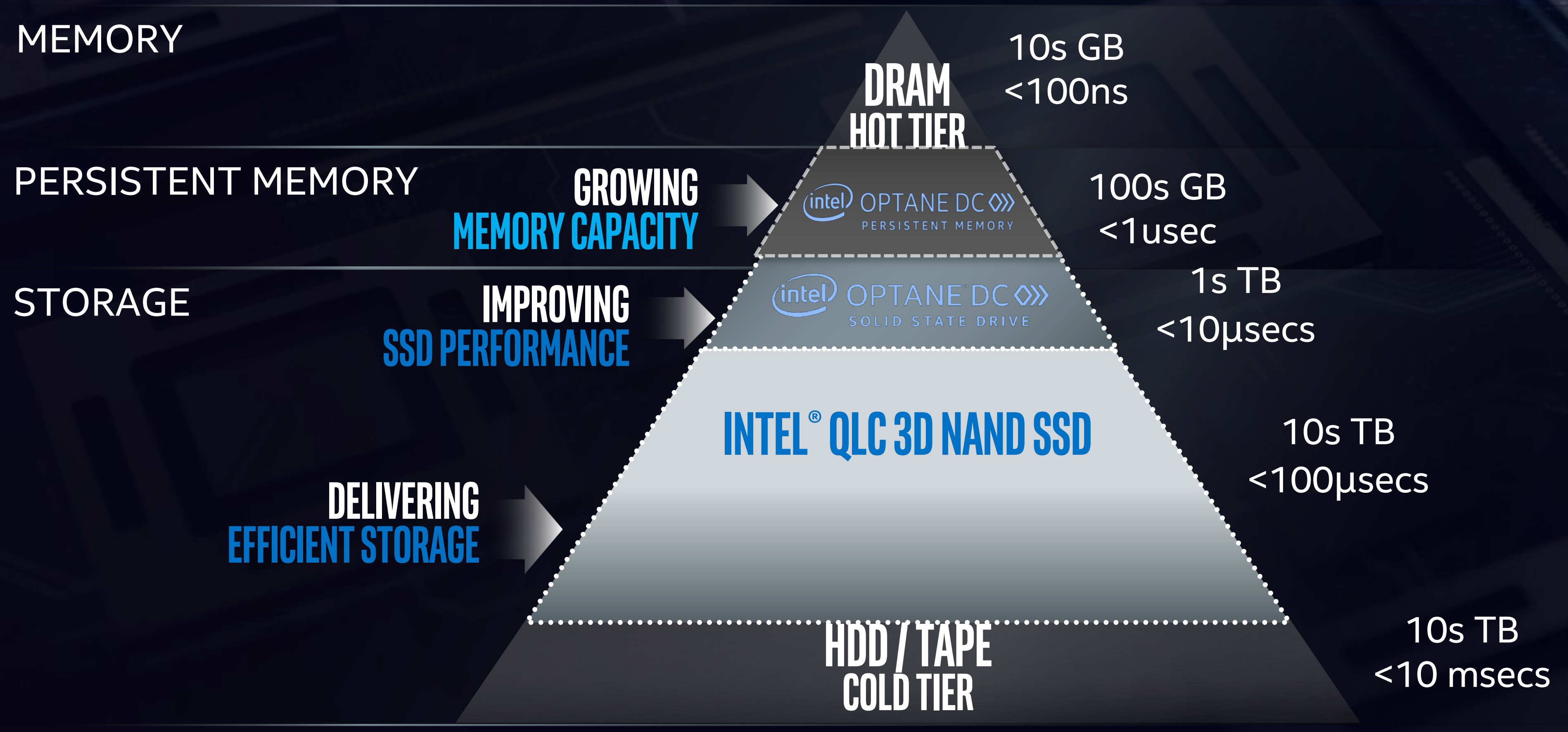


DATA STORAGE IN 1PB IN 1U

w/INTEL® 3D NAND SSDs

Under embargo until Dec. 12, 2018 at 6:01 AM PST unless a later date is specified

COMPLETE IN PERFORMANCE, CAPACITY, FIT



SNIA PERSISTENT MEMORY PM SUMMIT

JANUARY 24, 2019 | SANTA CLARA, CA

Converging Memory and Storage

Frank Hady, PhD
Fellow, Intel Corporation
Chief Systems Architect, NVM Solutions Group